PROJECT DOCUMENT COVER SHEET

THERMAL COMFORT AND
TOLERANCE DESIGN CRITERIA

(NASA-TM-84849) THERMAL COMFORT AND TOLERANCE DESIGN CRITERIA (NASA) 43 p
N82-77222
Unclas
00/54 33938

REPORT NUMBER: BRO DB-57-67
DATE: 9/13/67

PREPARED BY:	James M. Waligora *James M. Waligora*
APPROVED:	(BRANCH AND/OR SUPPORT OFFICE) Edward L. Michel *Edward L. Michel*
APPROVED:	(DIVISION) Lawrence F. Dietlein, M.D. *L. F. Dietlein, M.D.*
APPROVED:	(PROGRAM OFFICE)

NO. OF PAGES ______

REVISIONS

DATE	PREPARED BY	APPROVALS: BRANCH	APPROVALS: DIVISION	APPROVALS: PROGRAM OFFICE	CHG. LETTER
10/3/68	J. M. Waligora	*ELM*	*LFD*		A
3/11/70	J. M. Waligora	*[illegible]*	*E.L.M*		B

REPORT NUMBER

TABLE OF CONTENTS

Comfort Criteria for use in Computer
Program Evaluation of Environments

Comfort is not easily defined in terms of physical or even physiological parameters. There are sense organs in the skin that enable man to judge hot and cold sensations, but there is no single sense organ by which to judge comfort. The Transient Metabolic Simulation Program predicts information on the rate of positive or negative heat storage in the body and the total heat storage of the body relative to a zero heat storage at 98.6 core temperature and 93.0 $\bar{x}$ skin temperature. Both these factors contribute to a feeling of comfort, along with local skin temperatures and skin temperature gradients along the surface of the body. Comfort is also associated with a number of nonthermal parameters including lighting, sound, smell, and touch. Deviations from comfort in any of these areas can affect the critical evaluation of thermal comfort.

The temperature limits stated in these criteria provide protection against both uncomfortable local skin temperatures and uncomfortable rates of positive or negative heat storage.

It should be understood that there are different levels of comfort and that individual missions may require more stringent limits for temperature control if they have a very long duration or if they require measurements made on a thermally stable man.

Criteria

Heat Storage: Zero BTU ± 65 BTU at a basal metabolic rate of 282 BTU/hr varying with metabolic rate as in Figure 1.

Basis: ± 0.5° F change in body temperature appears to be compatible with comfort and with minimal levels of sweating or shivering in a resting man and is predicted by the program when resting sea level comfort limits are input. The permitted increase in body temperature with exercise is based on computer simulation of heat storage when men are exposed to comfort limits determined at higher metabolic rates.

Requirement: Avoidance of discomfort associated with active levels of sweating or shivering at rest and with excessive levels of sweating at elevated metabolic rates.

Minimum Air Motion: 15 ft/min

Basis: Equal to minimum natural convection.

Requirement: Avoidance of dead air pockets of hot or cold air, dissipation of CO_2 and other waste gases and avoidance of large changes in convective heat loss with body movements.

Maximum Air Motion: 100 ft/min

Basis: Air motion above this level is subjectively drafty.

Requirement: To prevent uncomfortable local skin temperatures.

Air Motion and Activity:

Most tasks that increase metabolic rate effectively increase the air motion in relation to the man. Figure 2 provides nominal relative air velocities for different activities. Some activities may result in lower velocities while some, such as walking or running, may be much higher.

Minimum Humidity: 8 mm Hg pH_2O

Basis: The nasal and oral mucosa begin to dry between 8 to 10 mm Hg pH_2O.

Requirement: Avoidance of discomfort and nose bleeds.

Maximum Humidity: 95 percent Relative Humidity

Basis: At this humidity, liquid water is usually condensed on some surfaces. (Humidity does not affect a resting man at comfortable temperatures. At elevated metabolic rates where sweating may occur, humidity will be limited by comfortable air or wall temperatures.)

Requirement: Avoidance of discomfort and skin maceration due to the presence of liquid water.

Minimum Air Temperature: 60° F at 0.0 Clo decreasing linearly to 45° F at 1.0 Clo

Basis: Results of experiments in which low air temperatures are offset by high metabolic rates or radiation.

Requirement: To prevent uncomfortable cooling of any skin area.

Maximum Air Temperature: 100° F

Basis: Avoidance of high skin temperature.

Requirement: To prevent uncomfortable heating of any skin area.

Maximum Surface Temperature: 105° F

Minimum Surface Temperature: 55° F - 40° F

55° F - All metallic objects, all objects that are likely to be handled by the men, and all large wall areas.

40° F - Nonmetallic surfaces of limited area that are not likely to be contacted by the men.

Basis: Range within which contact with surfaces does not cause discomfort.

Requirement: To prevent overheating or overcooling of skin areas coming in contact with the surfaces.

Maximum Mean Radiant Temperature: 100° F

Minimum Mean Radiant Temperature: 60° F at 0.0 Clo decreasing linearly to 45° at 1.0 Clo.

Basis: Results of experiments in which low air temperatures are offset by radiation.

Requirement: To prevent uncomfortable cooling or heating of the skin.

Radiant Environment: In calculating radiant heat exchange with the environment, the computer program uses an input term, wall temperature. This term must not be considered to be the average wall temperature, rather the mean radiant temperature of the surfaces to which the man exchanges heat by radiation. This is particularly important to consider where the enclosure surrounding the man is large and has considerable variation in surface temperature. In such a case, mean radiant temperature must be calculated as the summation of the temperatures of areas surrounding the man multiplied by their subtended solid angle from the man divided by the total solid angle. It is possible for men in various areas of a large enclosure to experience quite different radiant environments.

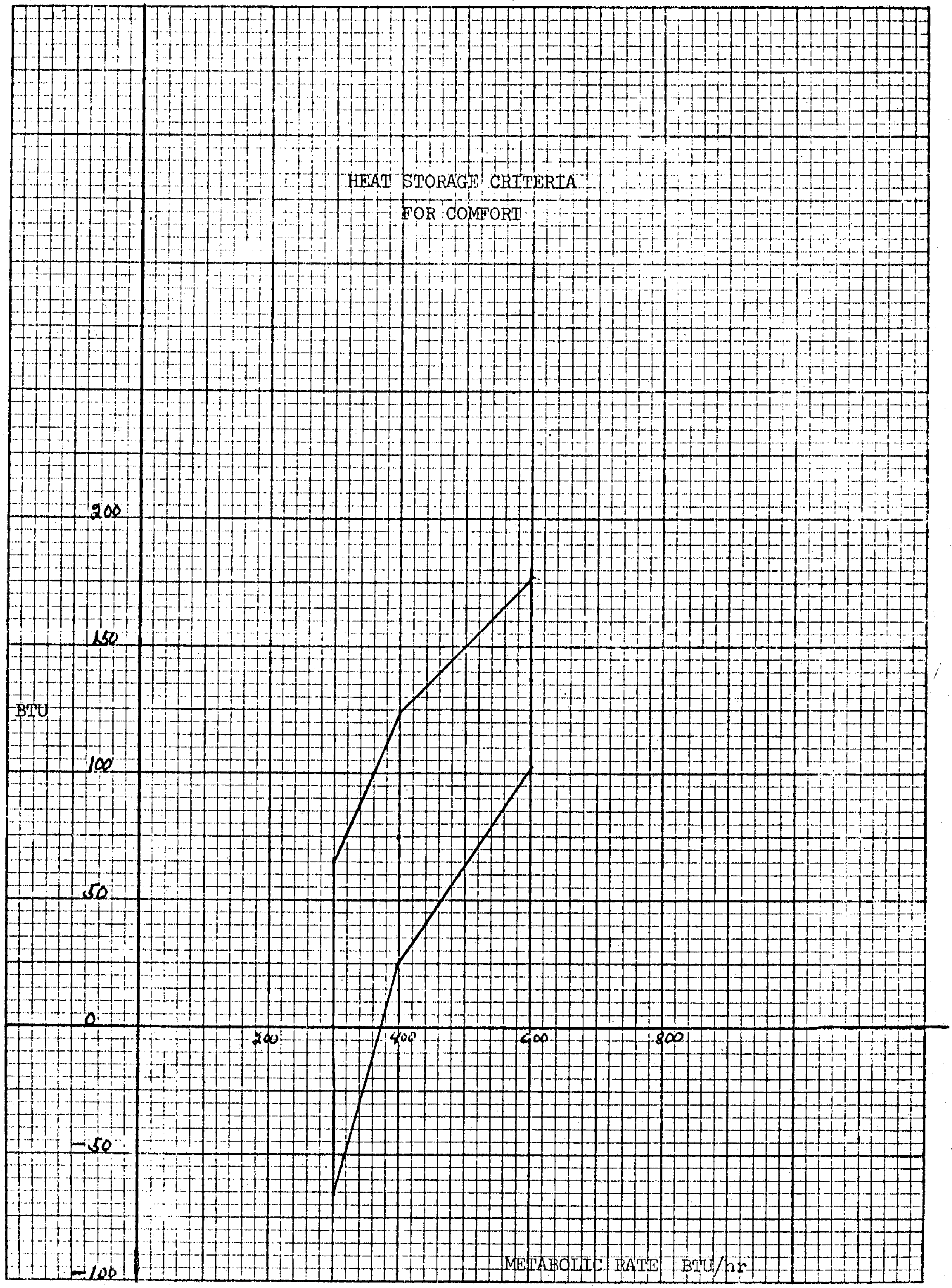
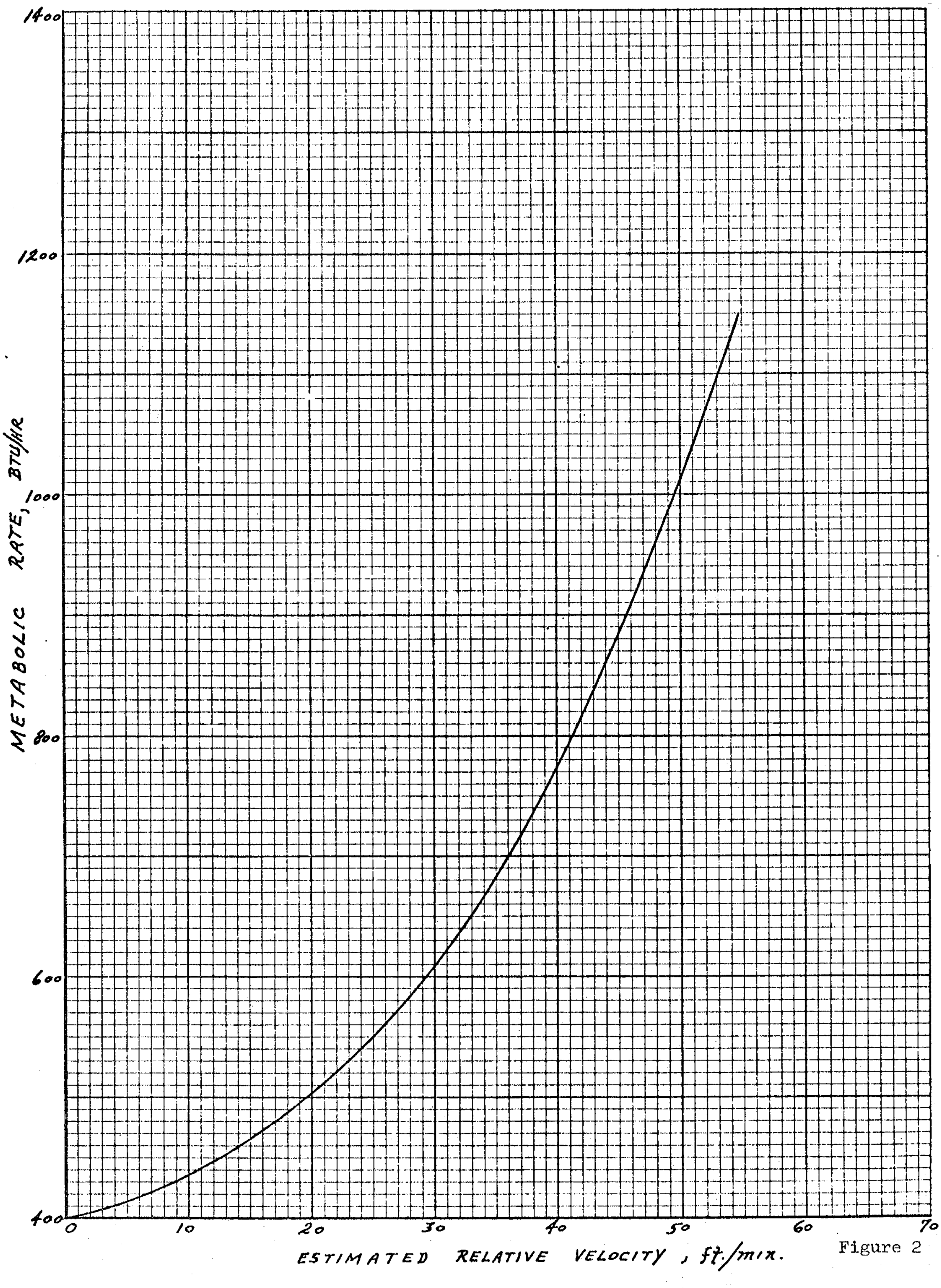

HEAT STORAGE CRITERIA
FOR COMFORT
200
150
BTU
100
50
0
200
400
600
800
-50
-100
METABOLIC RATE BTU/hr

Figure 1



1400
1200
1000
800
600
400
METABOLIC RATE, BTU/HR
0
10
20
30
40
50
60
70
ESTIMATED RELATIVE VELOCITY, ft./min.

Figure 2

Figure 3

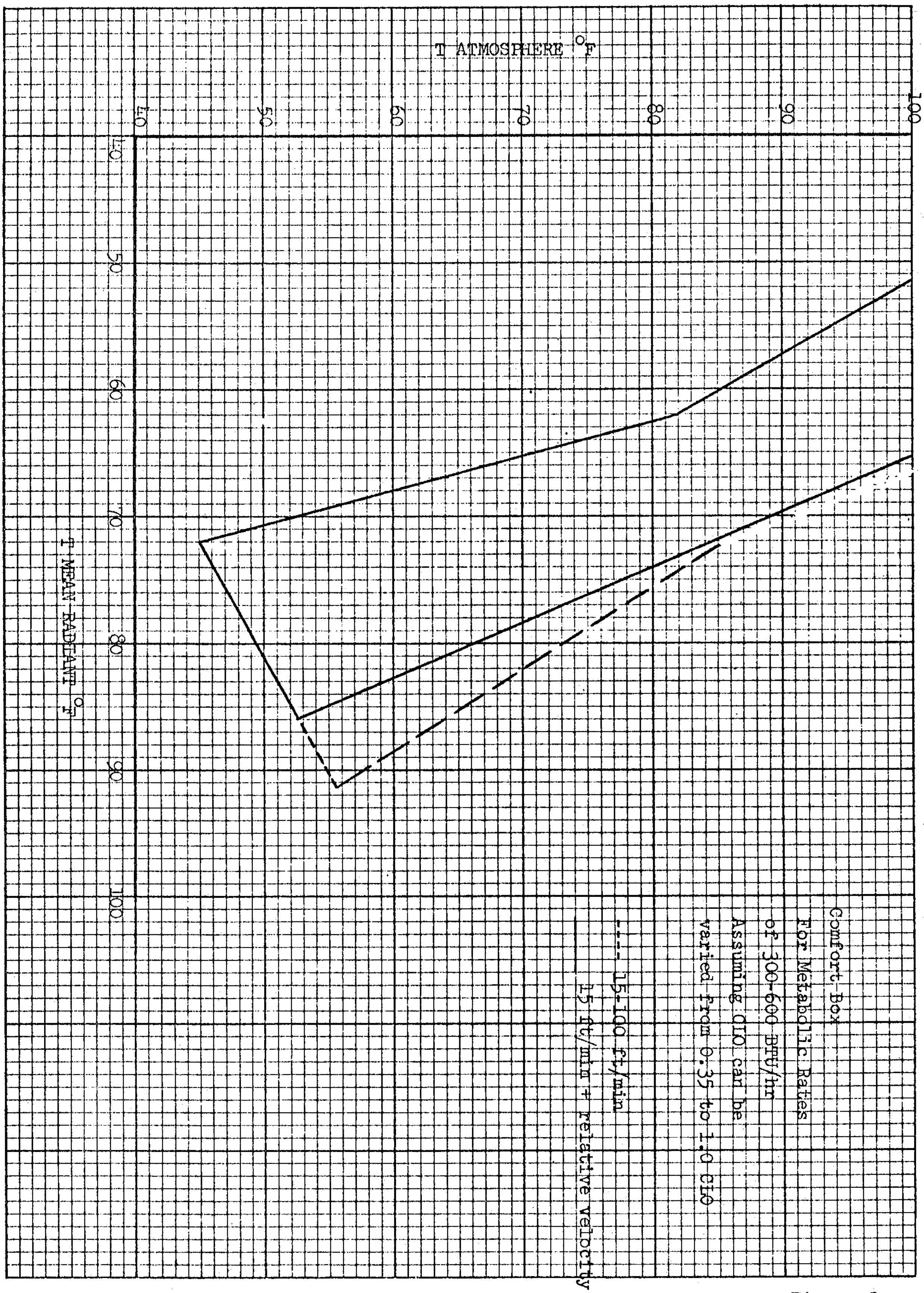


Figure 3

Application of Thermal Comfort Criteria in Defining The Requirements For The Orbital Workshop Thermal Environment

A series of computer runs have been made with the program to define a comfort box for the orbital workshop.

Inputs:

Metabolic Rate	300 BTU/hr, 600 BTU/hr
Work Efficiency	0
Clothing Emissivity	0.97
Windspeed	15 ft/min, 45 ft/min, 100 ft/min
Dewpoint Temperature	55^{o}
Atmosphere Temperature	45-100 ^{o}F
Mean Radiant Temperature	45-100 ^{o}F
Pressure	5.0 psia
Clothing	0.35 clo, 0.70 clo, 1.0 clo
Convective Area	19.5 ft^2
Radiative Area	15.5 ft^2

This comfort box provides a comfort range of approximately 10^{o} F. when atmospheric and mean radiant temperature are equal. Large deviations of atmospheric temperature can be offset by small deviations in mean radiant temperature and vice versa. In practice it seems unlikely that large deviations between atmospheric temperature and mean radiant temperature will occur except as transients. It should be emphasized that while provision can be made for individual control of the variables of windspeed and insulation, metabolic rate is not a controlled variable, therefore its variation constricts rather than enlarges the comfort box. The range of metabolic rate of 300 BTU/hr to 600 BTU/hr was chosen on the basis that 300 BTU/hr will be the approximate metabolic rate of a sleeping man. Six hundred BTU/hr is an approximate steady state maximum rate for mission work which will require 4 or more hours work. In constructing the comfort box two upper limits were used; one assuming no windspeed control uses an upper limit determined by air motion of 45 ft/min (15 ft/min + effective velocity of 30 ft/min at 600 BTU/hr, and a second curve using an air motion of 100 ft/min.

Operation Outside the Comfort Limits During Nominal Missions

Operation outside the limits of heat storage defined by the Thermal Comfort Criteria should be permitted only after it has been demonstrated that the situation cannot be corrected by ECS design. Any such excursion should be limited by the following restrictions:

1. Heat storage shall not deviate from the comfort zone by more than 65 BTU.

2. Continuous duration of exposure outside the comfort limits shall not exceed 1 hour.

3. The total duration of operation outside the comfort zone shall not exceed 120 minutes per day.

4. A decline in work performance shall be assumed during environmental excursion outside the comfort zone, and task scheduling shall be adjusted accordingly.

Tolerance Criteria for Use in Computer Program Evaluation of Environments

The performance of men at routine tasks has been shown to be at an optimum within fairly narrow comfort limits. Accordingly, the environment encountered by an astronaut during a failure-free mission should not fall outside the comfort range. Tolerance to temperature conditions outside the comfort range should become a design consideration only when a failure or emergency condition is considered. Tolerance to extremes of temperature is limited by temperatures causing tissue destruction in isolated areas of the body and also by positive or negative values of whole body heat storage which result in collapse or impairment of the ability of an individual to remove himself from the environment. The computer simulation with which the criteria set out in this document are to be used predicts heat storage, positive or negative, from set points of 98.6° F for the body core and 93.0° F for the skin. The computer program must treat thermoregulation as an isolated system and assume that the system cannot be fatigued. In reality, the stress that is activating the response of the thermoregulatory system affects other body systems which interact with thermoregulation. For this reason, periods of tolerable heat storage cannot be safely predicted beyond 4 hours. For emergency modes with durations in excess of 4 hours, comfort limits should be the design guide whenever possible. In those cases where it is not possible to remain within comfort limits, the acceptability of an emergency thermal environment should be determined by a manned test under maximum simulated conditions. In all emergency modes involving heat stress, water should be available to replace water lost by sweat.

Criteria

<u>Maximum Heat Storage</u>: +300 BTU

Basis: Above 300 BTU, the performance of tasks of mental complexity or high physical demand is sharply reduced. Above 400 BTU, some incidence collapse can be expected.

<u>Minimum Heat Storage</u>: -300 BTU

Basis: Below 300 BTU, shivering is continuous and very distracting and likely to severely limit performance.

<u>Maximum Surface Temperature</u>: 110° F

Basis: The maximum surface temperature is determined by the skin pain threshold of 113° F. Tolerance to skin temperatures in excess of 113° F is limited to seconds.

Minimum Surface Temperature: 40° F

Basis: There is a distinct risk of tissue damage when any part of the skin reaches 39° F.

Maximum and Minimum Air Temperatures and Mean Radiant Temperatures:

These factors become limiting whenever they combine to cause a local skin temperature to rise above 113° F or fall below 39° F. For small skin areas, a heat flux of about 18 BTU/ft^{2}min can be dissipated from an area by blood flow. In emergency cold modes if light clothing is worn whole body heat deficit of 300 BTU's is likely to occur before local skin temperatures limit tolerance. When cold is combined with wettedness for a period of several days, tissue damage can occur at temperatures as high as 55° F.

POSITION PAPER ON THERMAL COMFORT CRITERIA

Criteria for thermal comfort, based on computer simulation of man, have been recommended by the Biomedical Research Office for use as an Advanced Apollo design specification. The purpose of this paper is to describe the background of this specification, to discuss its requirements and limitations, and to establish the Medical Directorate position on these criteria.

1. NATURE OF THE CRITERIA

Through the years a considerable number of thermal indices have been devised. It is the purpose of the thermal comfort criteria provided not to replace existing thermal indices but to allow extrapolation of the limits of these indices to space environmental conditions while at the same time obtaining a more accurate estimate of the interacting body temperatures. In order to understand the application of these comfort criteria it is necessary to review some of the more important thermal indices.

The most widely used index of thermal comfort is the ASHRAE (American Society of Heating, Refrigerating, and Airconditioning Engineers) effective temperature index. This index was introduced in 1923 by Houghton and Yaglou (1). It is an empirical index based on subjective comparison of environments in adjacent rooms. The ASHRAE Laboratories and various contributors to ASHRAE have subsequently made subjective evaluations of comfort in different seasons and in different geographical areas and these studies have been used to periodically update the ASHRAE Comfort Chart. For quite some time it has been known that the conditions of the testing that established the effective temperature lines did not provide steady state evaluations, and, thereby, overemphasized the effect of humidity at low environmental temperatures and underemphasized the effect of humidity at high temperatures. The most recent version of the ASHRAE Comfort Chart incorporates steady state comfort lines determined by Koch, Jennings, and Humphries (2), as well as effective temperature lines.

The Wet Bulb Globe Temperature Index and the Wet Bulb Dry Bulb Index are both indices used because of simplicity and convenience and rely heavily on humidity as a measure of thermal stress. As such they are of practical value only at high temperatures where evaporation is of major importance.

McArdels P4SR Nomogram is a temperature index developed by the British Navy (3). This index empirically relates dry bulb, wet bulb, and globe thermometer temperatures, air speed, metabolic rate and clothing insulation to a measure of physiological strain imposed by the environment, in this case sweat rate. A direct correspondence between the P4SR index and sweat rate is only observed when a set of specified conditions are met.

Operative Temperature was introduced by Winslow, Herrington, and Gagge, in 1938 (4). Operative Temperature provides a means of evaluating a complex environment with different air and wall temperatures as equivalent to a reference temperature at which wall temperature is equal to air temperature at a standard air velocity. To determine Operative Temperature, a clothing or skin temperature is required as well as a knowledge of the environmental factors.

In 1945 an Air Force report entitled "Thermal Requirements for Aircraft Cabins" by Craig L. Taylor (5) presented a comfort chart which depicts the thermal requirements for tolerance and comfort in aircraft cabins. This chart is specific for light, seated activity, 1 clo of insulation, and an air motion of 200 FPM linear velocity. The ordinate of this chart is labeled Environmental Temperature, In the text of the report, however, Environmental Temperature is defined as an Operative Temperature with a reference air motion of 200 ft/minute. Methods are presented in the text to correct for different air speeds, pressures, and clothing assemblies. The tolerance limits on the graph were based on Effective Temperature lines corrected to the environmental condition of the chart, empirical data, or calculated negative heat storage depending on the type and duration of exposure being considered.

In 1954 in an Air Force report entitled "Prediction of Human Tolerance For Heat in Aircraft", Blockley, McCutchan, and Taylor (6) established tolerance limits for heat in aircraft based on empirical tests of less than one hour in which heat storage was measured. The design guide described how heat storage could be calculated from heat balance equations. Operative Temperature was used in this index and the temperature of the skin or clothing was determined by reiteration. In calculating heat storage in this index, it is assumed that there is no heat storage until the maximum heat loss capabilities are exceeded. This is not a serious fault when the exposures are such that tolerance is less than one hour, as in the empirical tests that define the heat storage limits in this index, because in this case the regulatory capacity of the man is exceeded almost as soon as the exposure begins. In less severe environments, however, considerable heat storage will occur in the man before the heat removal capacity of the environment is exceeded.

The last index that will be mentioned is an index based on the ratio of the amount of sweat evaporated to the amount of sweat that can be evaporated by an environment. In 1952, Belding and Hatch (7) developed this concept as an index for evaluation of industrial heat exposures. A similar approach was taken by Krontz and later modified by Burriss et al (8) for application as a spacecraft design guide. The major difficulty with the use of % evaporative capacity as an index is that in most cases the amount of sweat evaporated is more significant than the ratio, and the same ratio can be obtained in environments of clearly different physiological severity.

In considering these indices for a design guide for spacecraft, certain things become apparent. 1. The Revised ASHRAE Comfort Chart is the only comfort scale that has been determined by a large body of data consisting of subjective appraisal and any acceptable comfort criteria should concur closely with this chart. 2. The design criteria must take the thermal balance approach to estimating thermal state. Relying on some physiological response such as sweat rate is good for evaluating some preexisting condition, for instance the maximum duration of a watch in a hot station in a naval vessel. This is the use for which the P4SR Nomogram was designed, however, the empirical relationship of various environmental parameters to the limiting physiological parameter makes this index difficult to use as a design guide and even more difficult to modify for a different environment. 3. Design criteria using a thermal balance approach must incorporate some model of man, be it physical or physiological, that provides information as to the interface temperature of man with the environment or as in the case of the Belding and Hatch Index (7) it must assume a constant interface temperature.

The thermal comfort criteria provided bases both comfort and tolerance limits on body heat storage. The thermoregulatory model used in establishing the comfort criteria is one of a series of models developed by Dr. Stolwijk at the Pierce Foundation Laboratory. This model provides accurate simulation of steady state experiments. The Stolwijk model of thermoregulation was converted from its original analogue form to digital form by the Analytical Section of Crew Systems Division's Environmental Control Branch. Heat transfer equations were added to the model which allows computation of thermal balance and evaluation of different wall and air temperatures and different wind speeds and pressures.

The limiting range in mean body temperature for comfort was obtained by inputing the limiting conditions for comfort determined at sea level conditions at rest (9) and at various work rates (10) into the model and using the mean body temperature output as the limiting factor.

2. LIMITATIONS OF THE CRITERIA

The criteria established contains input limits on surface temperatures to insure that local areas of the body are not overcooled by conductive heat loss. Overcooling or overheating of this nature depends on the areas involved and the conductance and heat capacity of the surfaces. For the sake of simplicity, maximum and minimum mean radiant temperatures and surface temperatures were prescribed, rather than incorporate a complex analysis into the criteria. It is possible that specific exceptions to the surface temperature criterion could be allowed after further analysis or manned testing of the specific case.

The model of thermoregulation used in the criteria gives good simulation of steady state and transient conditions. However, the prediction of comfort on the basis of body temperature storage does not hold if rapid transients are involved. That is, a man who has a positive heat balance of ± 65 BTU and is suddenly exposed to a very cold environment will feel very uncomfortable before he reaches a negative heat balance of -65 BTU. Limitations on the maximum and minimum air and mean radiant temperature, however, tend to limit the occurrence and duration of conditions where a man could be uncomfortable with the predicted comfort zone.

3. REQUIREMENT FOR COMFORT

The comfort limits described by these criteria are not easy to maintain in a space vehicle and questions are repeatedly asked by the engineering staff relative to whether comfort is a reasonable requirement for a spacecraft. A considerable volume of work has been done on the effect of heat on performance. The performance of men at many different tasks have been observed at a variety of temperatures. There is considerable variation in the results of these tests. In general, where motivation is high, where the subject is skilled in his task and duration of exposure is short, performance can be maintained to a point just short of collapse. At the opposite extreme, if the task is such that motivation is difficult to maintain, exposure is prolonged and tasks are more unfamiliar, differences in performance can be measured even in the upper border of the comfort zone.

Pepler (12), in his summary review of the literature on performance in heat, makes the following comment, "Heat has many different effects on human skills, depending on the nature of the task performed, and on the degree of heat stress. There is evidence that moderate levels of heat have specific effect on the accuracy of skilled movements, interfere with the detection of small infrequent visual signals, and impair the performance of a number of intellectual tasks. Severe heat may have specific effects also, but a more general impairment of performance predominates which in some respects is reminiscent of the effect of cerebral anoxia." Decrements in performance in the cost have been reported to occur in cold conditions just as rapidly as in hot conditions (12).

An additional consideration in maintaining thermal comfort is that heat stress has been shown to interact synergisticly with other stresses such as acceleration, hypoxia, vibration, dehydration, and noise. The result of this interaction is that the tolerance level of the man for both stresses is reduced.

Although it is not possible to make a quantitative prediction as to the effect of discomfort on the performance of crewmembers, optimum performance can only be assumed for the condition of no thermal stress which corresponds with thermal comfort. The philosophy of manned space flight has been that man is an essential adjunct to space exploration because of his ability to evaluate situations and make judgements. If we intend to make full use of man's abilities, however, we must assure that his performance capabilities are not compromised by his environment.

4. TRANSIENT EXCURSIONS FROM LIMITS

In the design of a specific spacecraft for its mission it is possible and even probable that situations will present themselves where maintenance of comfort conditions appear to be impossible. In such a case three alternatives present themselves: Radical redesign of the vehicle, allowance for transient excursions outside the comfort range, or the provision of a life support device which will provide a comfortable microclimate. If the excursion of temperature from the comfort zone is extreme, redesign is the only reasonable solution. The provision of a life support garment with its associated equipment, is a complex design problem in itself and any such garment would likely hamper the functional capabilities of a crewman. The third alternative, operation outside the comfort zone, also has some very distinct disadvantages in that any excursion outside the comfort zone increases the level of body heat storage and decreases the tolerance time of the crewmen in the event of a thermal emergency. Further, in any excursion outside the comfort zone optimum performance cannot be assured. In view of these disadvantages any operation outside the limits of heat storage defined by the Thermal Comfort Criteria should be permitted only after it has been demonstrated that the situation cannot be corrected by ECS design. Any such excursion should be limited by the following restrictions: 1. Heat storage should never deviate from comfort limits by more than 65 BTU. 2. Continuous duration of exposure outside the comfort limits should not exceed one hour. 3. The total duration of exposure outside the comfort limits should not exceed 120 minutes/day. 4. A decline in work performance should be assumed during environmental excursion outside the comfort zone, and task scheduling should be adjusted accordingly.

5. SUMMARY

Criteria for thermal comfort have been established by this directorate. These criteria are based on the limitations of the environmental input to a model of thermoregulation in a man as well as limitations to the predicted variation in body temperature of the man. It is the position of this directorate that the criteria be used as a specification for Environmental Control system design for the Apollo Applications Program and beyond.

REFERENCES

1. Houghten, F. C., and C. P. Yaglou: ASHVE Research Report No. 673- "Determination of the Comfort Zone" ASHVE Transactions, 29, 1923, 361.

2. Koch, W., B. H. Jennings, and C. M. Humphreys. Environmental Study II--- "Sensation Responses to Temperature and Humidity under still air conditions in the comfort range". ASHRAE Transactions, 66, 1960, 264.

3. McArdle B., et al. Report 47/391, Royal Naval Personnel Research Committee, Medical Research Council, London, 1947

4. Winslow, C. E., Herrington, L. P., and Gagge, A. P., Amer. Jour. Physiol. 120, 1937, 1.

5. Taylor, G. L., Army Air Forces Headquarters Air Technical Service Command Engineering Division Memorandum Report on "Thermal Requirements for Aircraft Cabins", 31 August 1945.

6. Blockley, W. V., McCutchan, J. W., and Taylor, C. L., "Prediction of Human Tolerance for Heat in Aircraft: A Design Guide", WADC Technical Report 53-346, May 1954.

7. Belding, H. S., and Hatch, T. F., "Index for Evaluating Heat Stress in Terms of Resulting Physiologic Strains", Heating Piping and Air Conditioning, 27, p. 129, 1955.

8. Burriss, W. L., "Study of the Thermal Processes for Man in Space", NASA CR. - 216, April 1965.

9. Nevins, R. G., Rohles, F. H., Springer W., and Feyerherm, A. M., "A Temperature-Humidity Chart for Thermal Comfort of Seated Persons", ASHRAE Journal, p. 55, April 1966

10. McNall, P. E., Jax, I., Rohles, F. H., Nevins, R. G., and Springer, W., "Thermal Comfort (Thermally Neutral) Conditions for Three Levels of Activity" ASHRAE TRANS., 73, 1967

11. Siple, P. (1945) quoted in: "The Effects of Thermal Stress on the Human Body", D. McK. Kerslake in: A Textbook of Aviation Physiology, ed., J. A. Giles; Pergamon Press, N. Y., 1965.

12. Pepler, R. D., "Performance and Well-Being in Heat" in: Temperature Its Measurement and Control, In Science and Industry, Part 3, Vol. 3, ed., J. D. Hardy, Reinhold Publishing Corporation, New York, 1963, p. 319.

PHYSIOLOGIC APPRAISAL OF ACCEPTABLE MINIMUM
WATER VAPOR PRESSURE LEVELS FOR SPACEFLIGHT

Problem:

a. BRO has recommended a minimum water vapor pressure of 8 mm Hg be a design specification for the Advanced Apollo program.

b. From engineering viewpoint it would be advantageous to allow a lower acceptable limit since cold areas anticipated in the SA IV B Workshop would require heating in order to prevent condensation.

c. Since, unfortunately, the NASA Bioastronautics Data Book indicates that water vapor pressures as low as 5 mm Hg are acceptable the BRO has been asked by the engineers to provide some relief to the recommended design specification, if possible.

Background:

The skin of the body is not an impermeable layer. Water is lost from the body in a comfortable environment by diffusion through the stratum corneum and possibly by a residual level of sweat gland secretion. The tone and condition of the outer surface skin is due in part to the diffusion of water from below and in part to the loss of water vapor from the surface of the skin. The effect of excessively low water vapor pressure in an environment is chapping and fissuring of the skin, drying of mucous membranes in the nose and throat and drying with a resulting burning sensation of the conjunctiva of the eye. A secondary effect of drying of the mucous membranes is an increase in the likelihood of respiratory infection.

The following description of the effect of humidity on respiratory infection is quoted from a report by Cramer (1966): (1)

"The lining of the upper respiratory tract is equipped with cilia, hairlike structures of microscopic size with a wavelike motility, which carry a blanket of mucus with which they are covered toward the posterior pharynx where it is swallowed."..."The nasal mucus which has a 97 percent water content, is more viscous than mucus elsewhere in the body and even slight drying increases the viscosity enough to interfere with the work of the cilia. The restriction or absence of moisture, even for a matter of minutes, may destroy the cilia which then must be regenerated. In the meantime there is a piling up and thickening of the mucous blanket due to a lack of ciliary action. In this gelatinous state the mucus affords an excellent culture medium where the infection agent can flourish and is able to penetrate the lining membrane, with the resulting respiratory infection."

Limits on water vapor that have proposed for aerospace use include 10 $\pm$ 5 mm Webb, 1964 [2], 5 mm - 10 mm Webb, 1965 [3], and 10 mm $\pm$ 3 mm Billimgham 1960[4]. The humidity limits that were specified for Project Apollo were a minimum of 40% relative humidity and a maximum of 70% through a temperature range of 70° F to 80° F. These relative humidities are equivalent to 7.5 mm to 13 mm at 70° F and 10.5 to 18.5 mm at 80° F. Liese (1933)[5] found that subjective reports of excessive dryness were made by the occupants of a centrally heated office block at 68° F when relative humidity fell below 25% (5 mm Hg). Summarizing ASHRAE Comfort data Nevins 1965[6] comments that "in the range of 73° F to 78° F the effect of humidity on their comfort and well being has been found to be negligible over a range of humidities of 25% to 70%." On the other hand Winslow et al (1942)[7] measured dryness of the mucosa at the back of the throat and found that the membranes were moist at 10 mm Hg but dry at 7.5 mm Hg. A number of doctors concerned with the nose and throat and respiratory infections have recommended vapor pressures on the order of 10 mm [8,9,10].

An interacting factor in the space environment is the low total pressure. Although the rate of evaporation of water depends only on the difference in water vapor pressure between the skin surface and the boundary layer of adjacent air, the total pressure can effect the concentration of water vapor in the film next to the skin. A study by Hale, Westland, and Taylor[11] at different altitudes indicates that insensible water loss from the skin is increased at high altitudes. Long duration Gemini missions have resulted in reports by the crewmem of nasal drying and stuffiness[12]. Some of this nasal and pharyngeal congestion has been noted in the long duration space cabin simulator runs in a similar environment. The symptoms reported would not be expected to occur at sea level at the humidities experienced in the spacecraft. Whether the drying of the mucous membranes was due in part to reduced pressure or to some other factors in the environment such as the O_2 or the weightlessness is not clear. In any case it appears that drying of the mucous membranes is more of a problem in spaceflight than at sea level conditions.

<u>Conclusions</u>:

1. Although at sea level conditions subjective discomfort is not noticed above water vapor pressures of 5 to 6 mm Hg, there is evidence that the functions of the mucous membranes in the nose and throat are impaired at water vapor pressures below 8 mm Hg with increased likelihood of respiratory infection.

2. The experience obtained in long duration Gemini flights indicates that there are factors in the spacecraft environment that accelerate drying of the mucous membranes in the nose and throat.

<u>Recommendation</u>:

That the previously recommended lower limit of water vapor pressure for a nominal mission of 8.0 mm Hg be implemented as an Advanced Apollo Applications Design Specification.

REFERENCES

1. Cramer, I. I., "Atmospheric Moisture Content and Respiratory Mucous Membrane." Annals of Allergy Vol. 24, p. 552, 1966.

2. Webb, P., "Thermal Balance, Heat Tolerance, and Protection" in Bioastronautics, ed., Karl E. Schaefer, the Macmillan Company, New York, p. 116, 1964.

3. Webb, P., "Water Vapor as a Critical Component in Sealed Cabins and Pressure Suits." in: Humidity and Moisture Measurement and Control in Science and Industry, Volume 2, Applications, ed., Elias J. Amdur, Reinhold Publishing Corporation, New York, p. 78, 1965.

4. Billingham, J. and D. McK. Kerslake, "Specification for Thermal Comfort in Aircraft Cabins." Flying Personnel Research Committee, Memo 133, Institute of Aviation Medicine, Royal Air Force, Farnborough, 1960.

5. Liese, W., 1933,quoted in: A Textbook of Aviation Physiology, ed., J. A. Gillies, Pergamon Press, New York, p. 450, 1965.

6. Nevins, R. G. and James D. Hardy, "Humidity Effects on the Comfort and Well-Being of People." in: Humidity and Moisture Measurement and Control in Science and Industry, Volume 2, Applications, ed., Elias J. Amdur, Reinhold Publishing Corporation, New York, p. 10, 1955.

7. Winslow, C. E. A., L. P. Herrington and A. P. Gagge (1942) quoted in: Temperature and Human Life, C. E. A. Winslow and L. P. Herrington, Princeton University Press, Princeton, New Jersey, p. 194, 1949.

8. Andrews, A. H., Jr., Clinical Cardiopulmonary Physiology, Grune & Stratton Inc., New York, p. 258, 1957.

9. Proetz, A. W., M.D., "Humidity a Problem in Air Conditioning", Annals of Otology, Rinology, and Laryngology, Vol. 65, p. 376, 1956.

10. Hitschler, W. J., M.D., "Humidification Indoors in Winter", Archives of Otolarygology, Vol. 72, 1960.

11. Hale, F. C., R. A. Westland and C. L. Taylor, "The Influence of Barometric Pressure and Vapor Pressure on Insensible Weight Loss in Nude Resting Man", WADC Technical Report 57-9, 1957.

12. Berry, C. A., M.D., "Man's Response to Long Duration Flight in the Gemini Spacecraft" in: Gemini Midprogram Conference, NASA SP-121, p. 247, 1966.

Thermal Comfort and Tolerance Design Criteria
for Application to Shuttle Design

To provide a guide to temperature control design in shuttle, this addendum to BRO-DB-57-67 has been prepared which includes warm and cool comfort limits for possible shuttle ambient pressures.

The purpose of this addendum is not to revise the Comfort Criteria but to use the Criteria to generate limiting curves for pressures, windspeed control, and various insulations of clothing assemblies that might be applicable to shuttle design. The same procedure was used to generate comfort limiting curves that was used to generate the comfort limits for the orbital workshop, contained in the main body of the Comfort Criteria. The source data for the comfort data was mentioned and referenced in the Comfort Criteria; however, the data was not presented directly. It should be emphasized that the basis of the Comfort Criteria is the sea level comfort data collected at Kansas State University at the ASHRAE Laboratory. In using this data the following summary data points were input into the 14 node Transient Metabolic Simulation Program:

Work Efficiency	= 0	Dewpoint Temperature	= 55° F.
Clothing	= 0.6 clo	Pressure	= 14.7 psi
Clothing Emissivity	= 0.97	Convective Area	= 19.5 ft^2
		Radiative Area	= 15.5 ft^2

Metabolic Rate: 389, 622, 829, 1061

Windspeed:

Metabolic Rate	Windspeed
389 BTU/hr	30 ft/min
622 BTU/hr	45 ft/min
829 BTU/hr	54 ft/min
1061 BTU/hr	66 ft/min

Air and Wall Temperatures:

Metabolic Rate	Cool Limit	Warm Limit
389 BTU/hr	74° F.	84° F.
622 BTU/hr	64° F.	75° F.
829 BTU/hr	60° F.	73° F.
1061 BTU/hr	56° F.	68° F.

From the output of the program a curve was generated relating body heat storage to metabolic rate at limiting upper and lower temperatures based on the following computer generated outputs:

Metabolic Rate	Cool Limit	Warm Limit
389 BTU/hr	2 BTU	120 BTU
622 BTU/hr	77 BTU	177 BTU
829 BTU/hr	165 BTU	235 BTU
1060 BTU/hr	235 BTU	283 BTU

The appropriate heat storage for 300 BTU/hr, a metabolic rate representative of sleeping for 400 BTU/hr, and for 600 BTU/hr were obtained by interpolation and extrapolation. The values used in the analysis were -65 BTU, +65 BTU for 300 BTU/hr, +5, +125 for 400 BTU/hr, and 75 BTU, 175 BTU for 600 BTU/hr. The +65 BTU, -65 BTU heat storages at 300 BTU/hr are representative of comfort limits of 76° F. to 86° F. for the reference sea level conditions.

The high and low temperature limiting curves were then generated by the computer using all combinations of mean radiant temperature and gas temperature that give the limiting heat storage outputs.

The warm limit in each case was determined for 600 BTU/hr metabolic rates. The air motions used for the warm limits were 100 ft/min and 45 ft/min (15 ft/min background + 30 ft/min effective velocity). The clo values used for the warm limit were 0.35 and 0.70. The 0.70 clo is representative of a typical two layer uniform while the 0.35 is representative of a one layer garment.

The cool limits were defined for a sleeping condition of 300 BTU/hr with 1.0 clo and 15 ft/min.

In addition, cool limits were also defined for 400 BTU/hr, a resting metabolic rate with clothing insulation of 0.7 clo and 1.0 clo and with windspeeds of 15 ft/min and 45 ft/min.

The 1.0 clo is typical of a two layer uniform with jacket or sweater or a medium weight business suit with jacket.

The design requirements that might be generated from these upper or lower limits will depend on capability and practicability of controlling windspeed and capability for provision of a variable insulation clothing assembly.

Windspeed control is practical where individual control can be provided for individuals located in a specific area for fairly long periods of time such as a sleep station, a work station, or a passenger seating area. It is rather impractical where crewmen must move freely about a large area.

In the range of temperatures which are comfortable the humidity is of little importance and need not be considered beyond the limitive constraints contained in the comfort criteria.

The upper and lower limits of the comfort curves have been arbitrarily cut off at 60° F. and 90° F. for both air and wall temperature. There is evidence that even greater differences in air and wall temperature would be acceptable. However, experience with a Skylab specification that permitted offsetting temperatures of 50° to 100° F. indicated that such wide offsets were of no practical use for steady state designs and tended to cause needless concern among those who did not completely understand the specification.

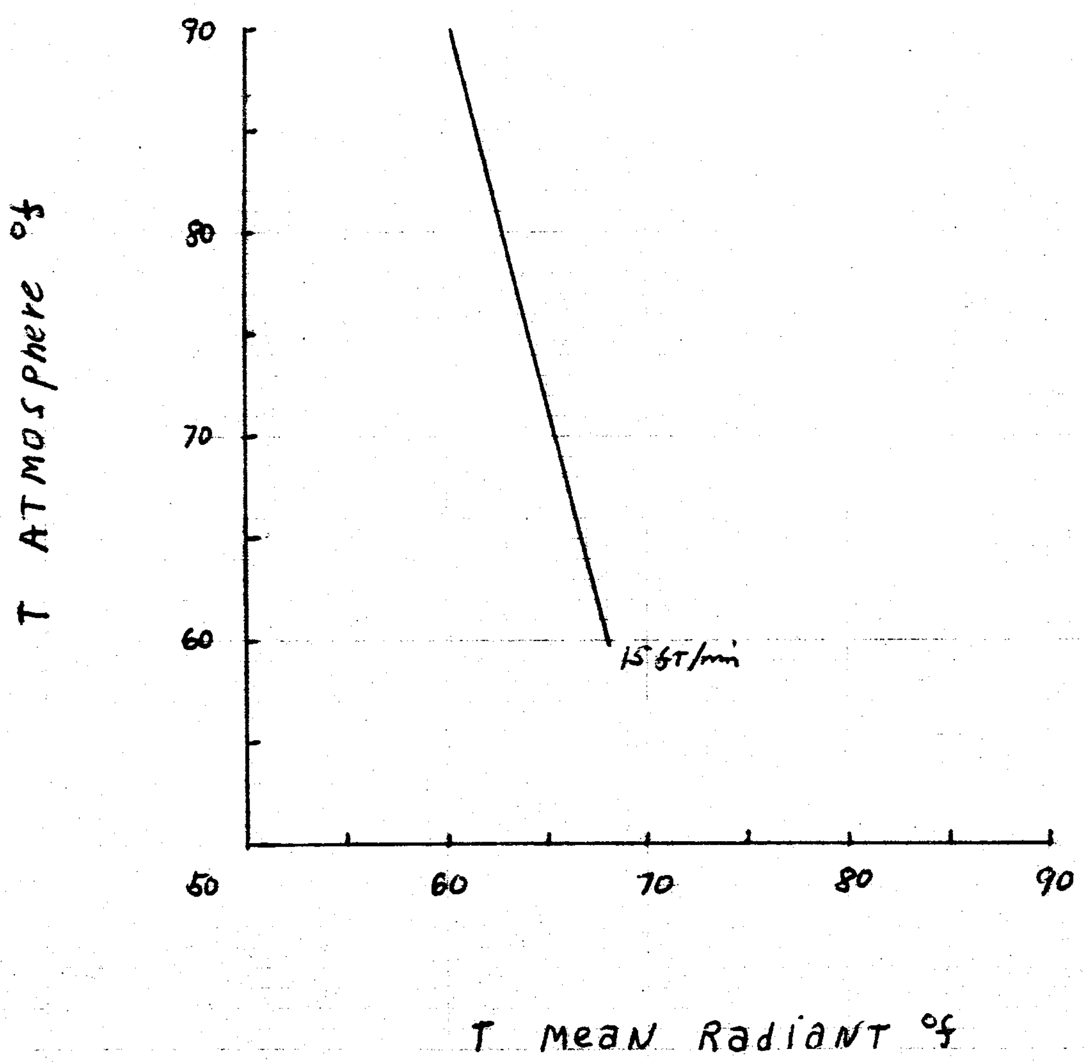
In addition, examples of the construction of a comfort envelope have been provided at each of the three pressures. In these examples clothing insulation was considered a controlled variable from 0.35 clo to 1.0 clo and windspeed was considered uncontrolled with a range of 15 ft/min to 45 ft/min.

It should be emphasized that the comfort criteria is applicable to steady state conditions and that the metabolic rates considered are averages for 4 hours or more.

In all spacecraft to date design has included the possibility of heat pulses during reentry, although in Gemini and Apollo the actual temperature pulses in the cabin were never much above the comfort level. In addition, post landing contingencies included 48 hour stay in an environment considerably above the comfort levels. However, the requirement for the crew to fly and land the shuttle vehicle means that crew performance is more critical than in prior post reentry phases and in addition, the crewmen are likely to be subjected to acceleration stresses at the same time. It is the recommendation of the Medical Directorate that the thermal environment be maintained within comfort limits during the post reentry phase. If this is not possible it is recommended that the response of crewmen to the reentry temperature profile and any coincident stresses be tested to insure that performance is not degraded. This is consistent with the post landing thermal tests on Gemini and Apollo where unavoidable thermal stress was combined with motion stress and possible cardiac deconditioning.

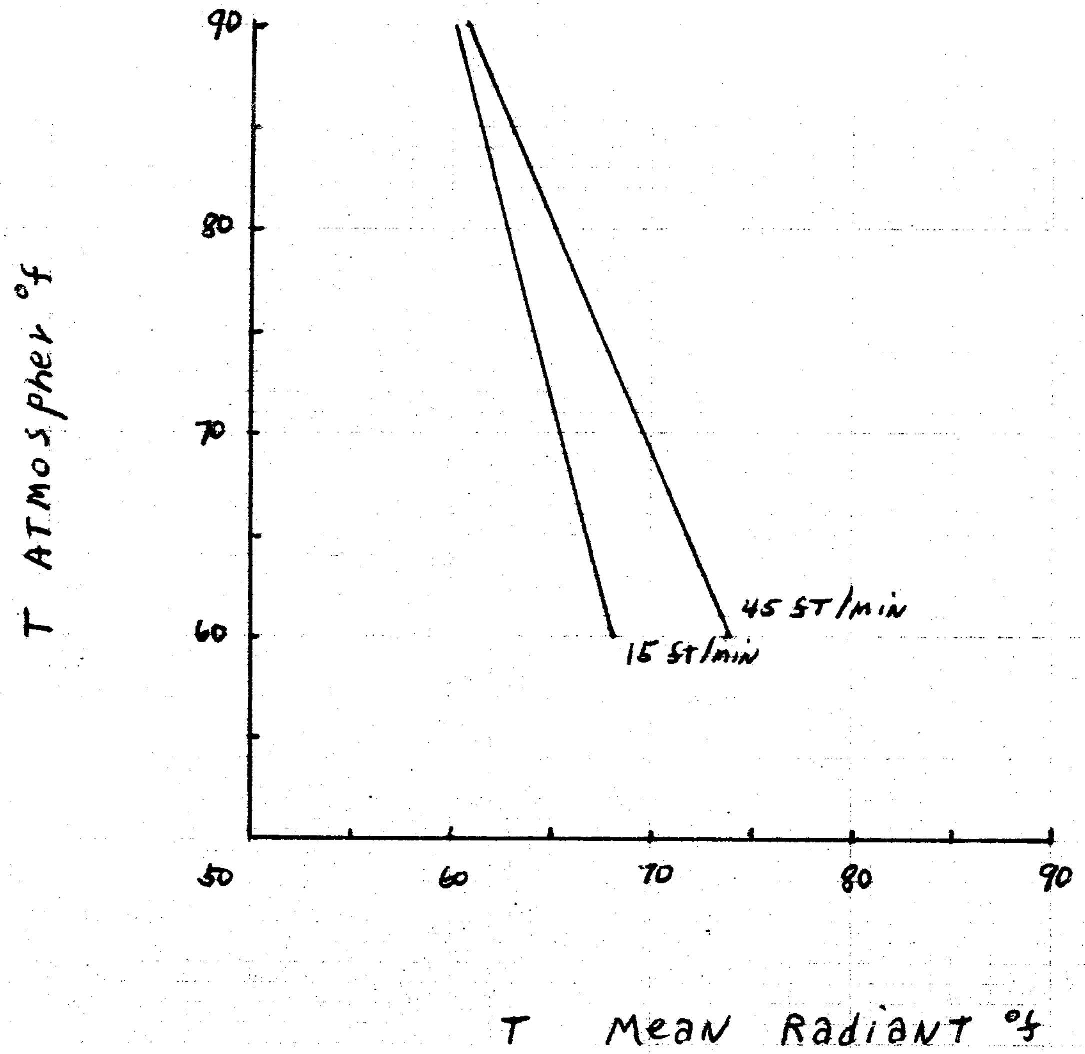
COOL LIMIT

300 BTU/hr
5.0 psia
1.0 CLO



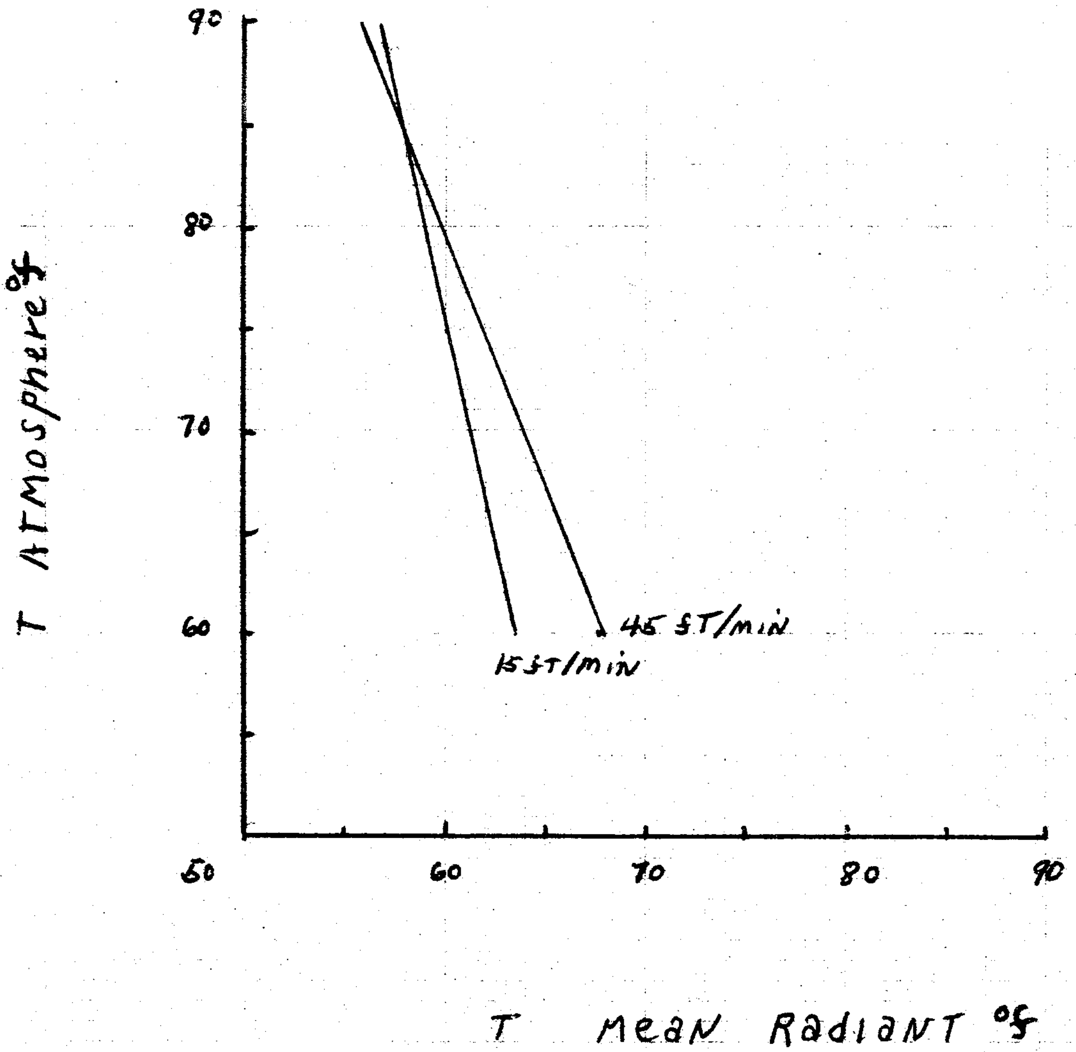
COOL LIMIT

400 BTU/hr
5.0 PSIA
0.7 CLO



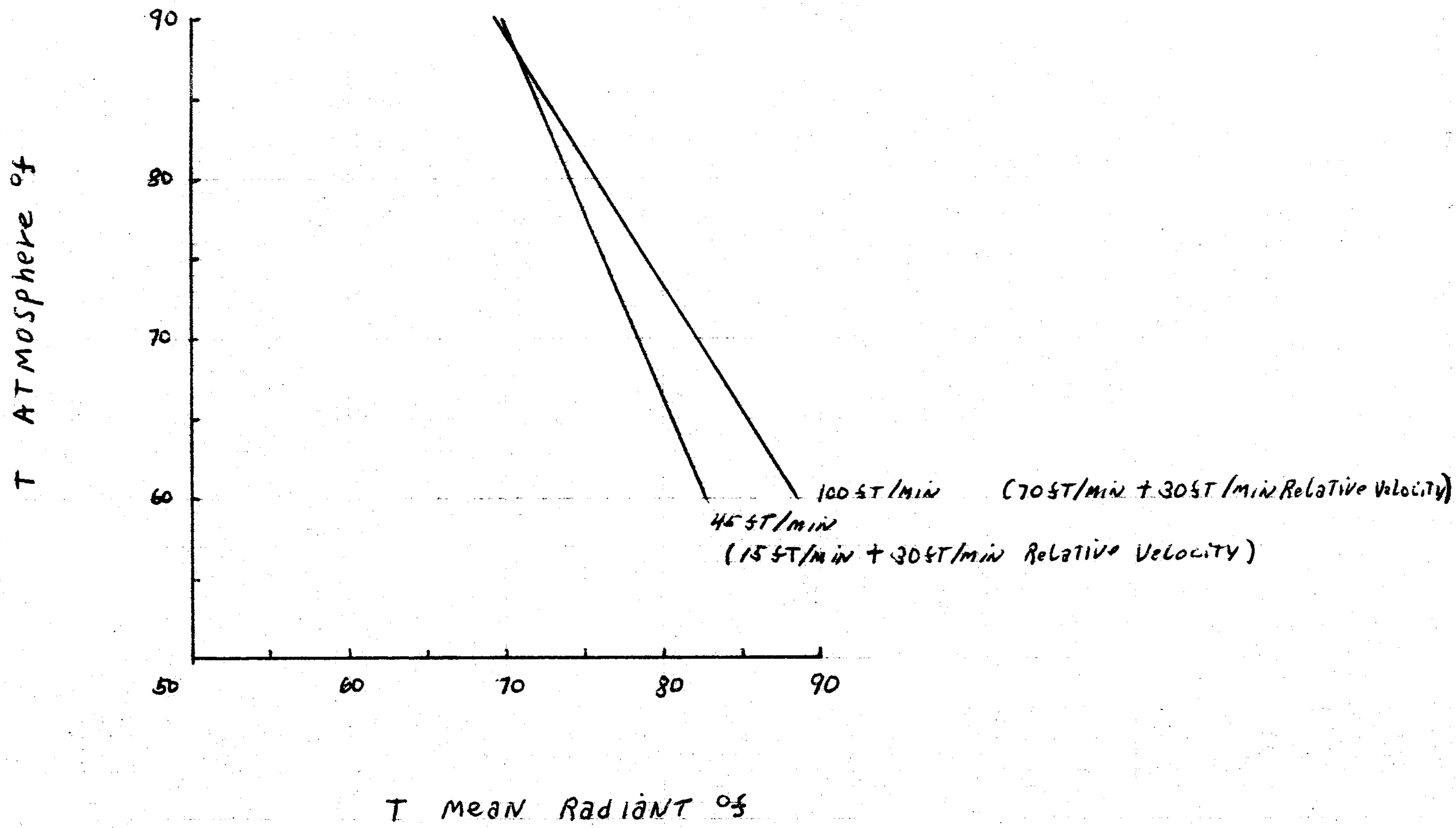
COOL LIMIT

400 BTU/hr
5.0 PSIA
1.0 CLO



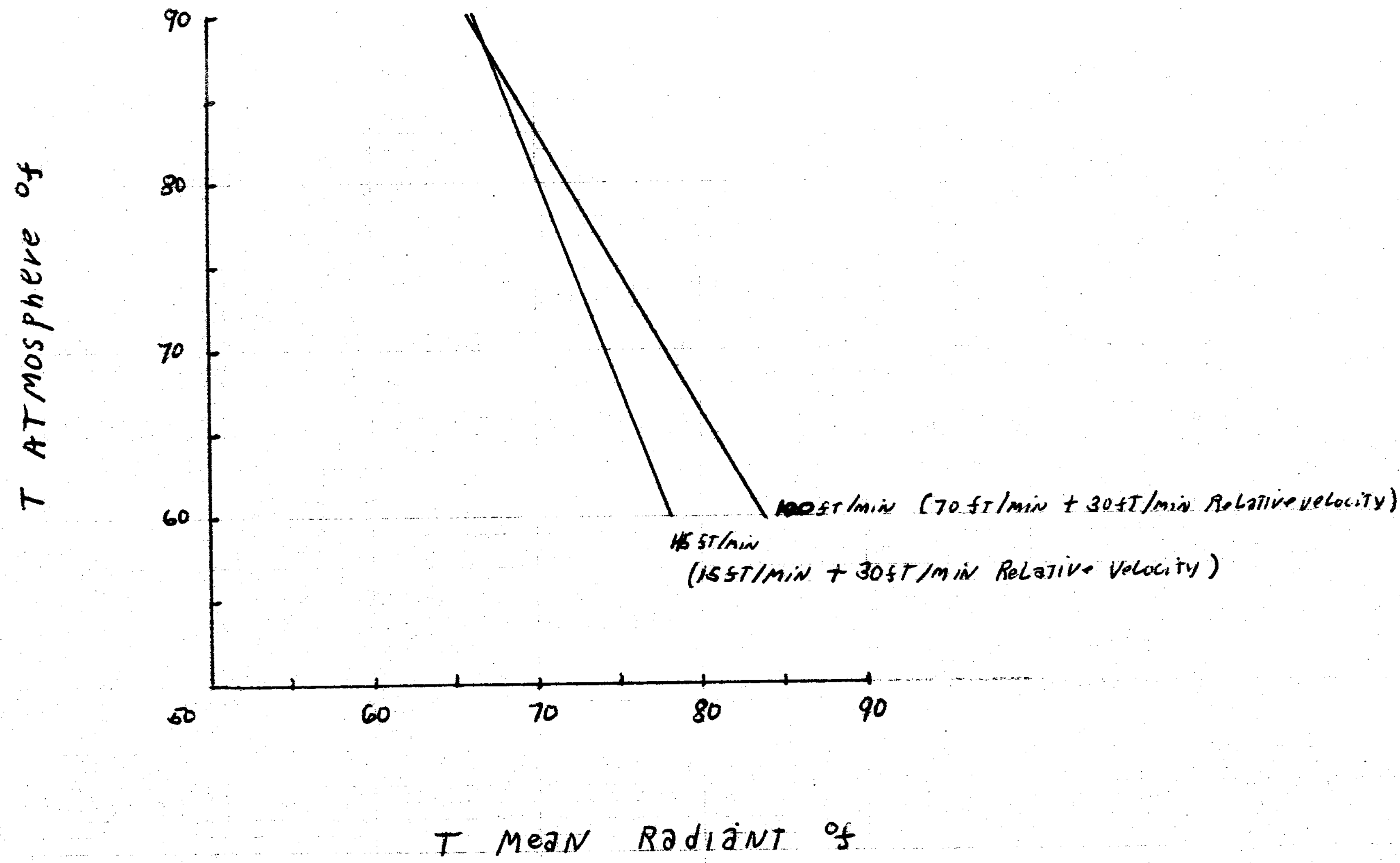
Warm Limit

600 BTU/hr
5.0 psia
0.35 CLO



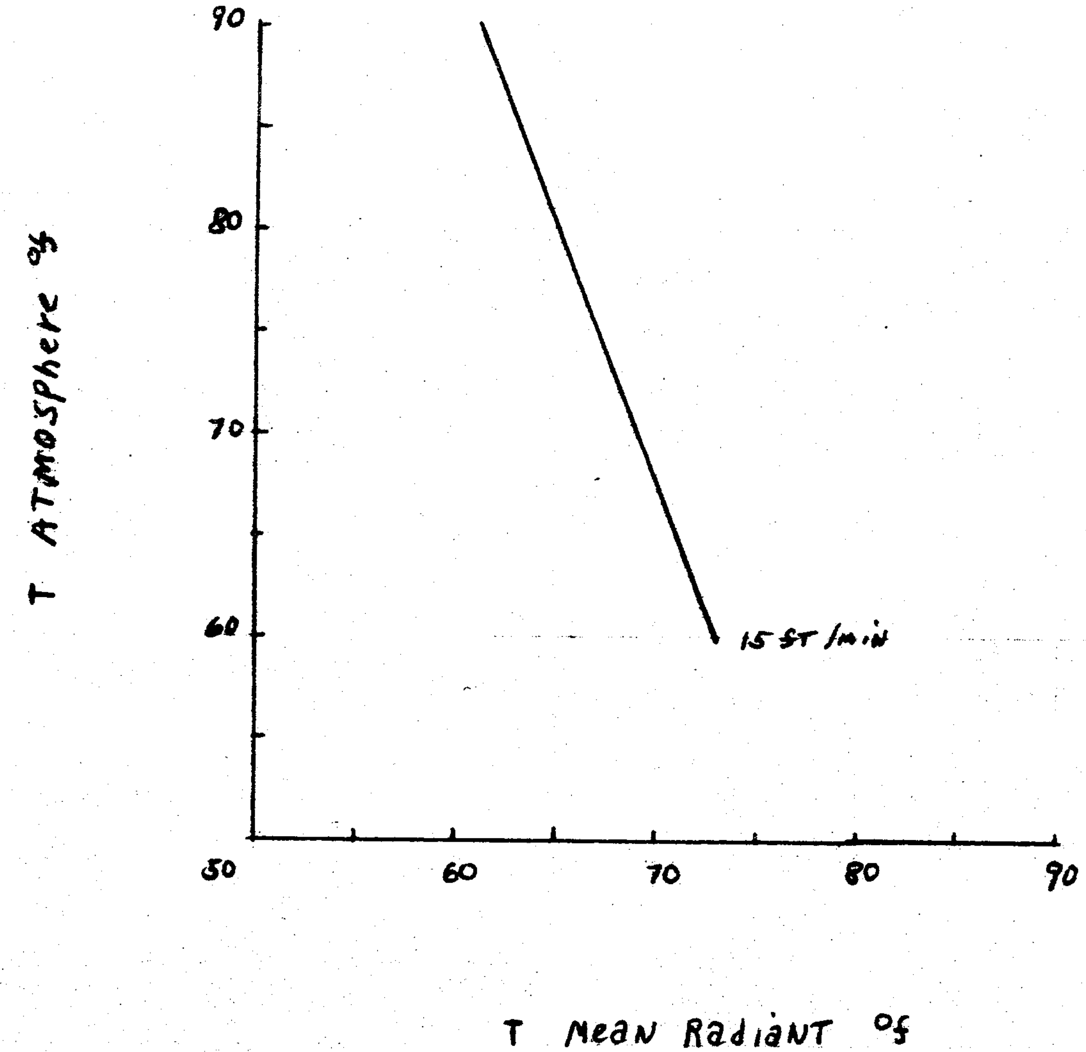
Warm Limit

600 BTU/hr
5.0 psia
0.7 CLO



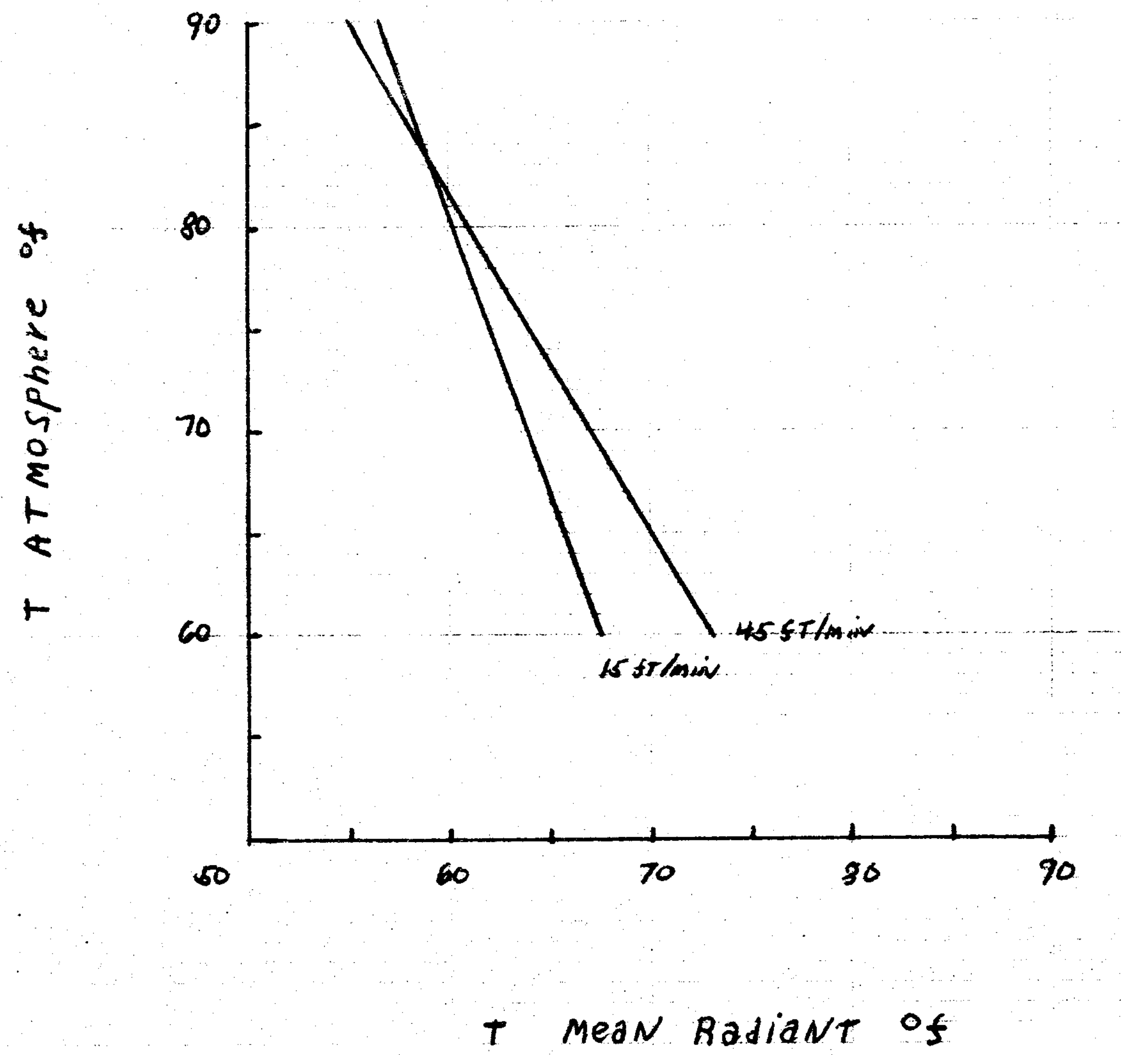
COOL LIMIT

300 BTU/hr
10 PSIA
1.0 CLO



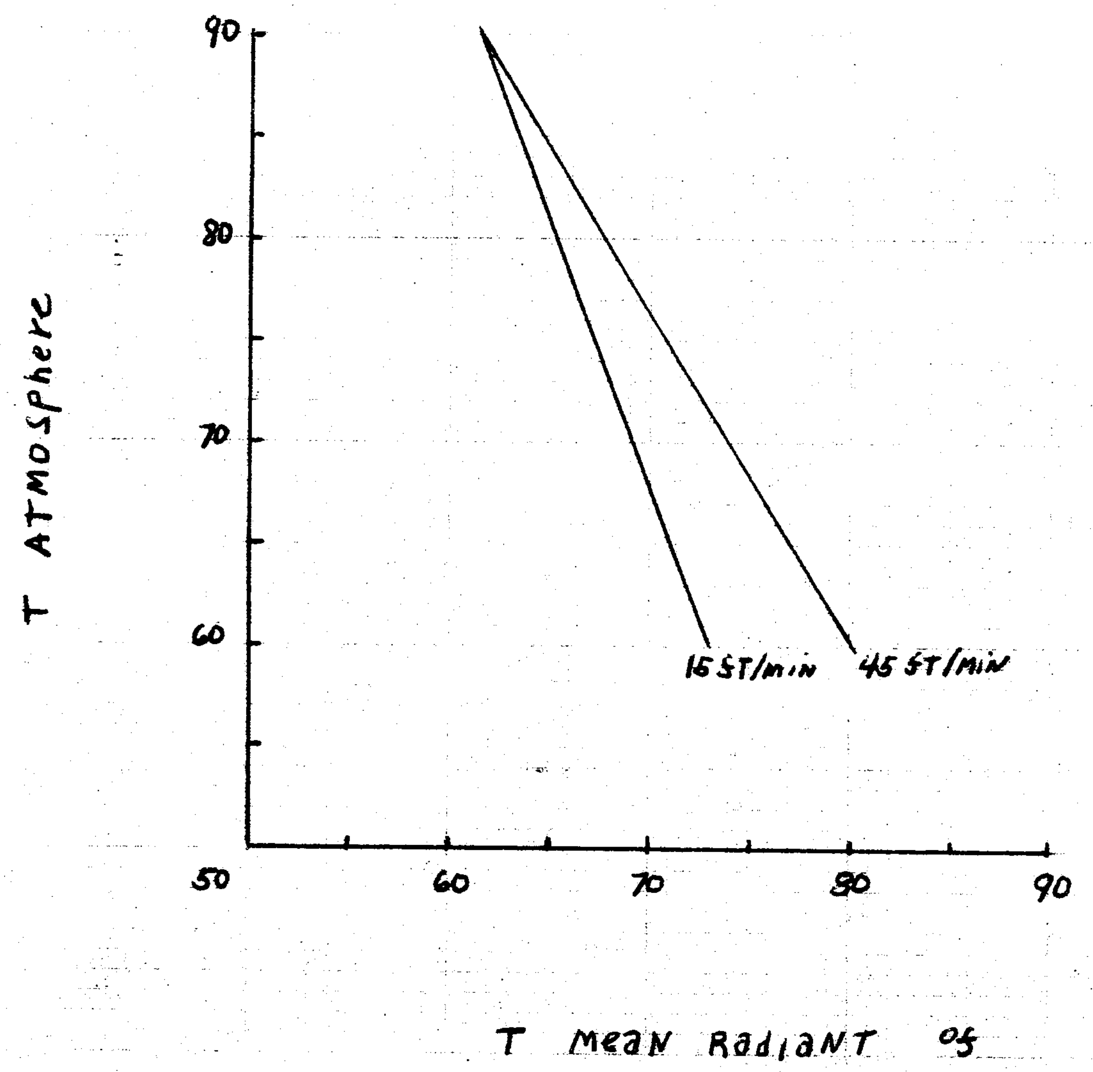
COOL LIMIT

400 BTU/hr
10 PSIA
1.0 CLO



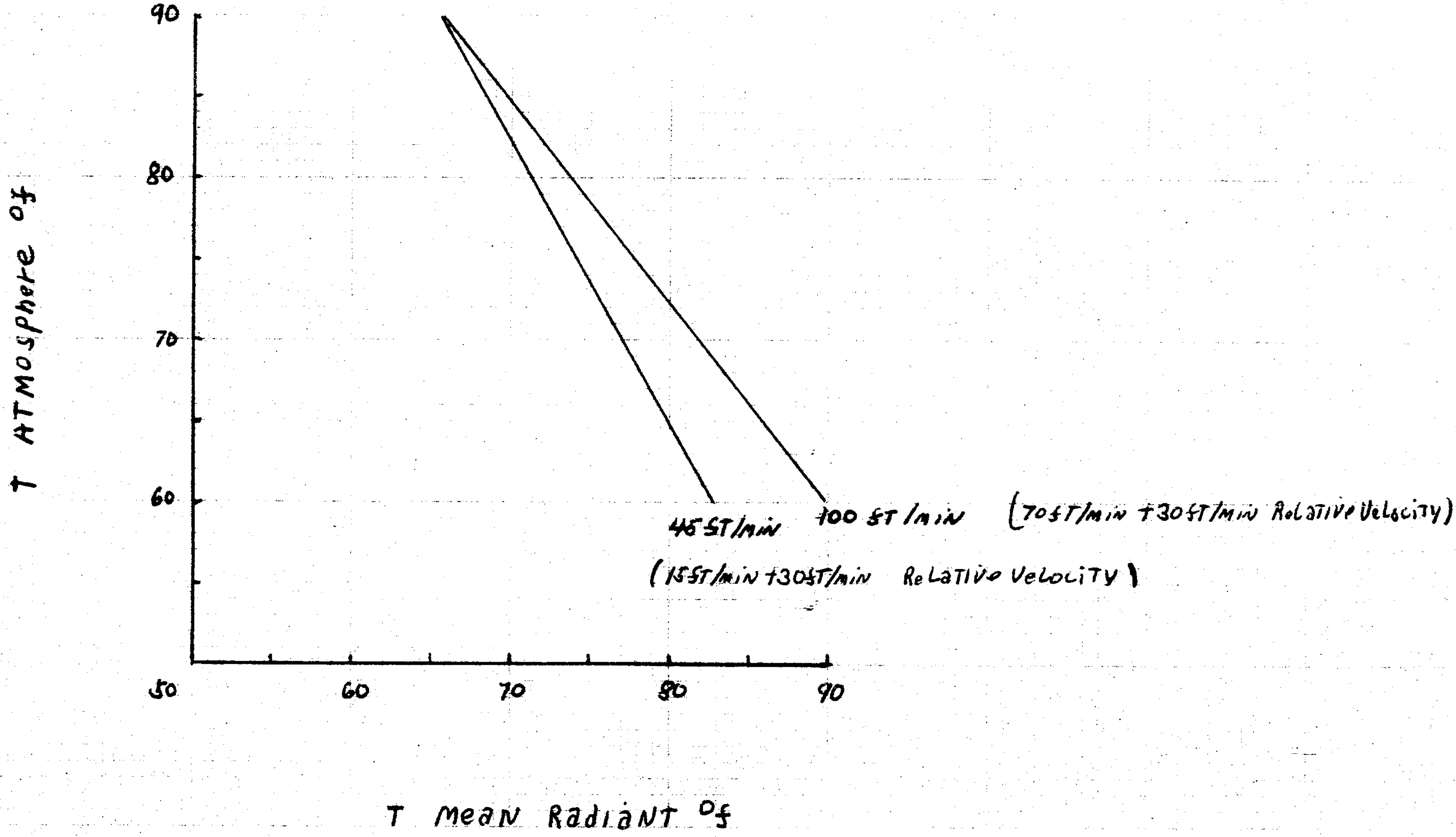
COOL LIMIT

400 BTU/hr
10 PSIA
0.70 CLO



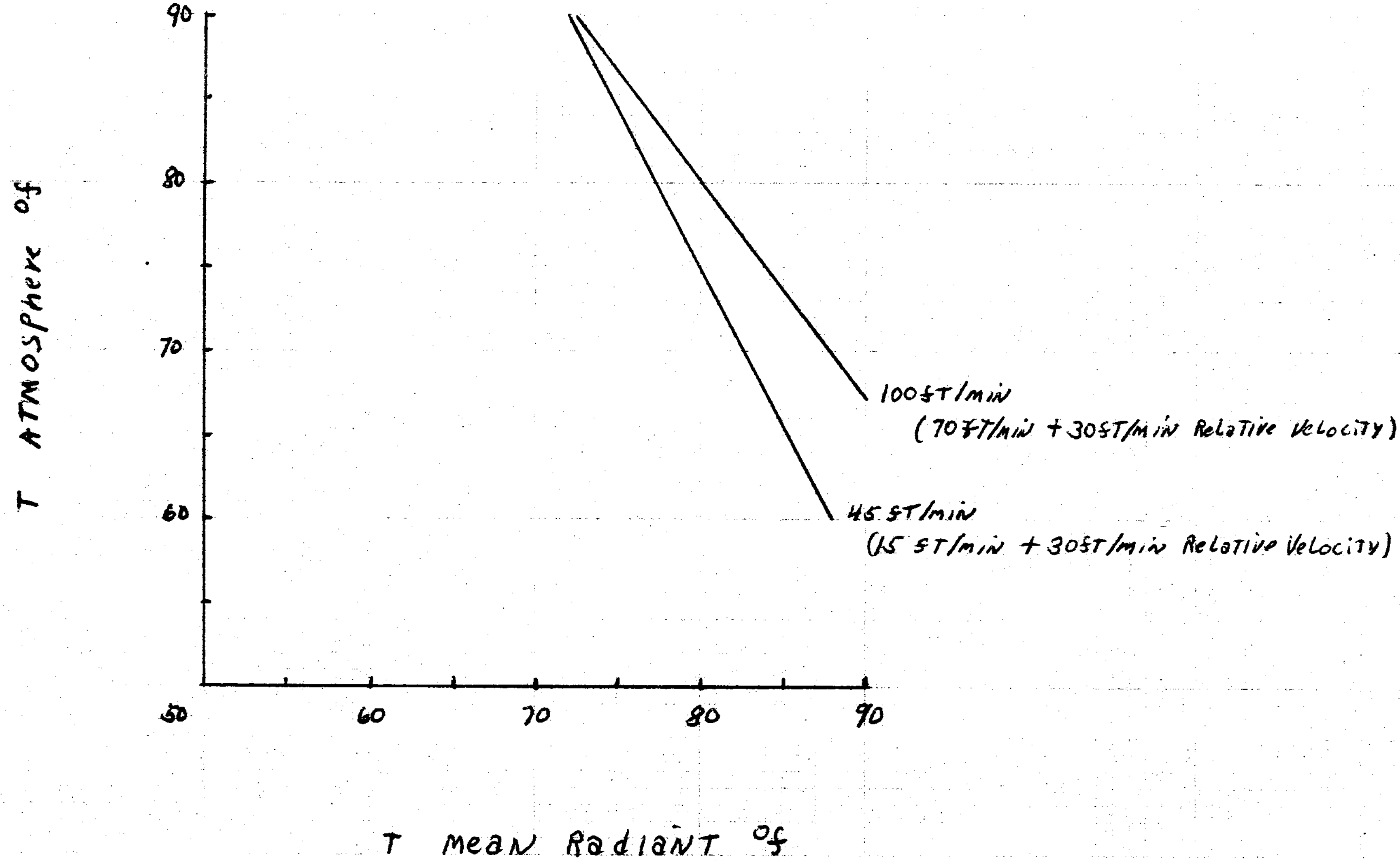
WARM LIMIT

600 BTU/hr
10 PSIa
0.7 CLO



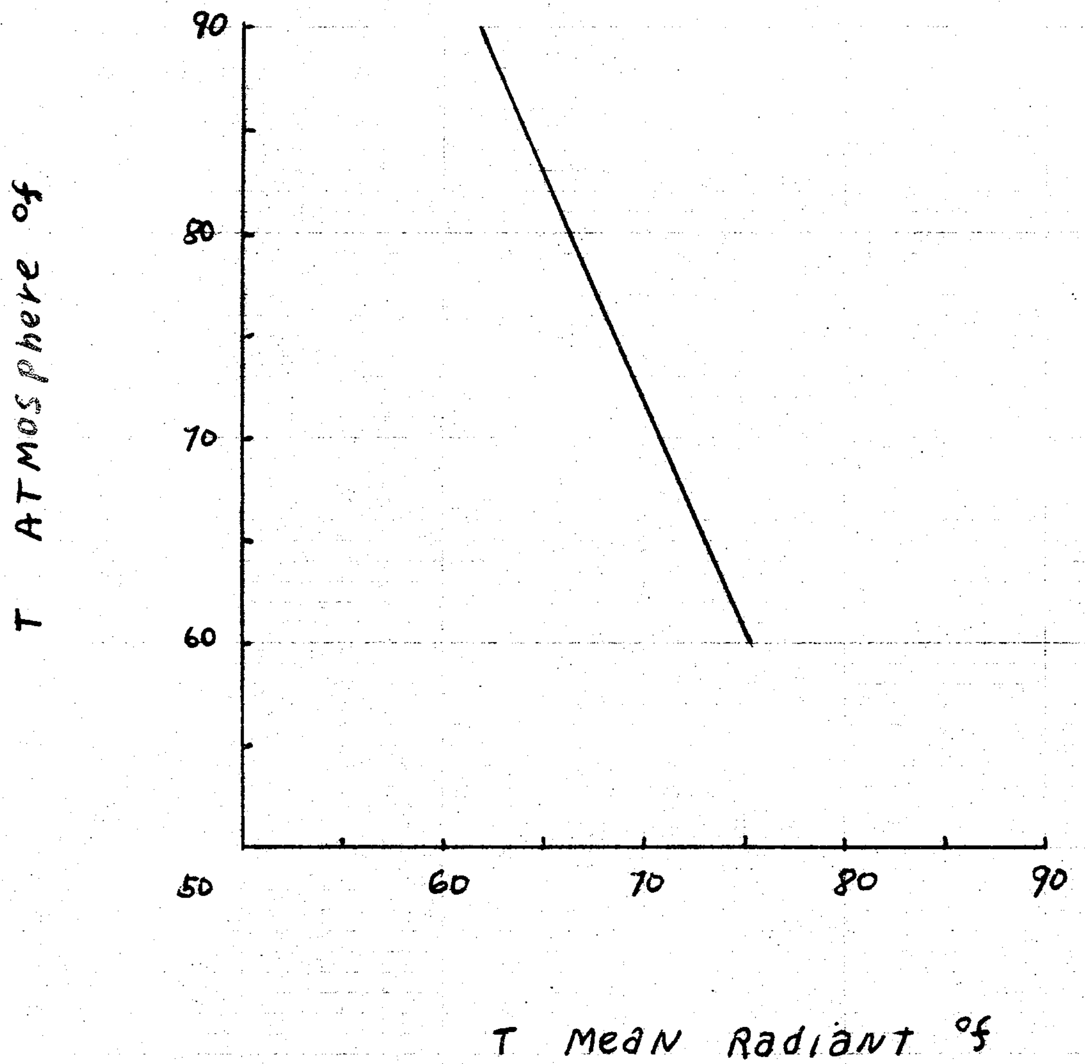
Warm Limit

600 BTU/hr
10 psia
0.35 CLO



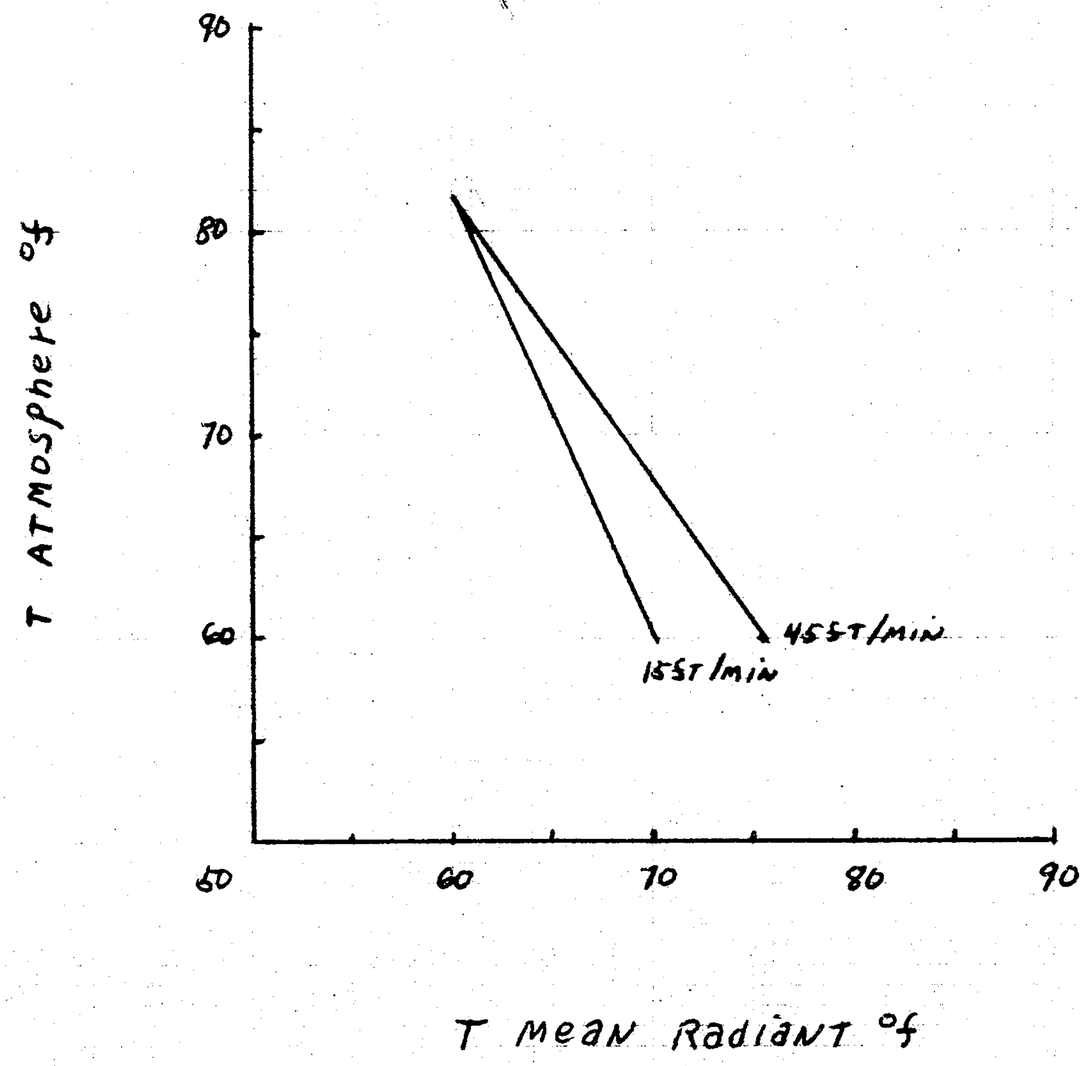
COOL LIMIT

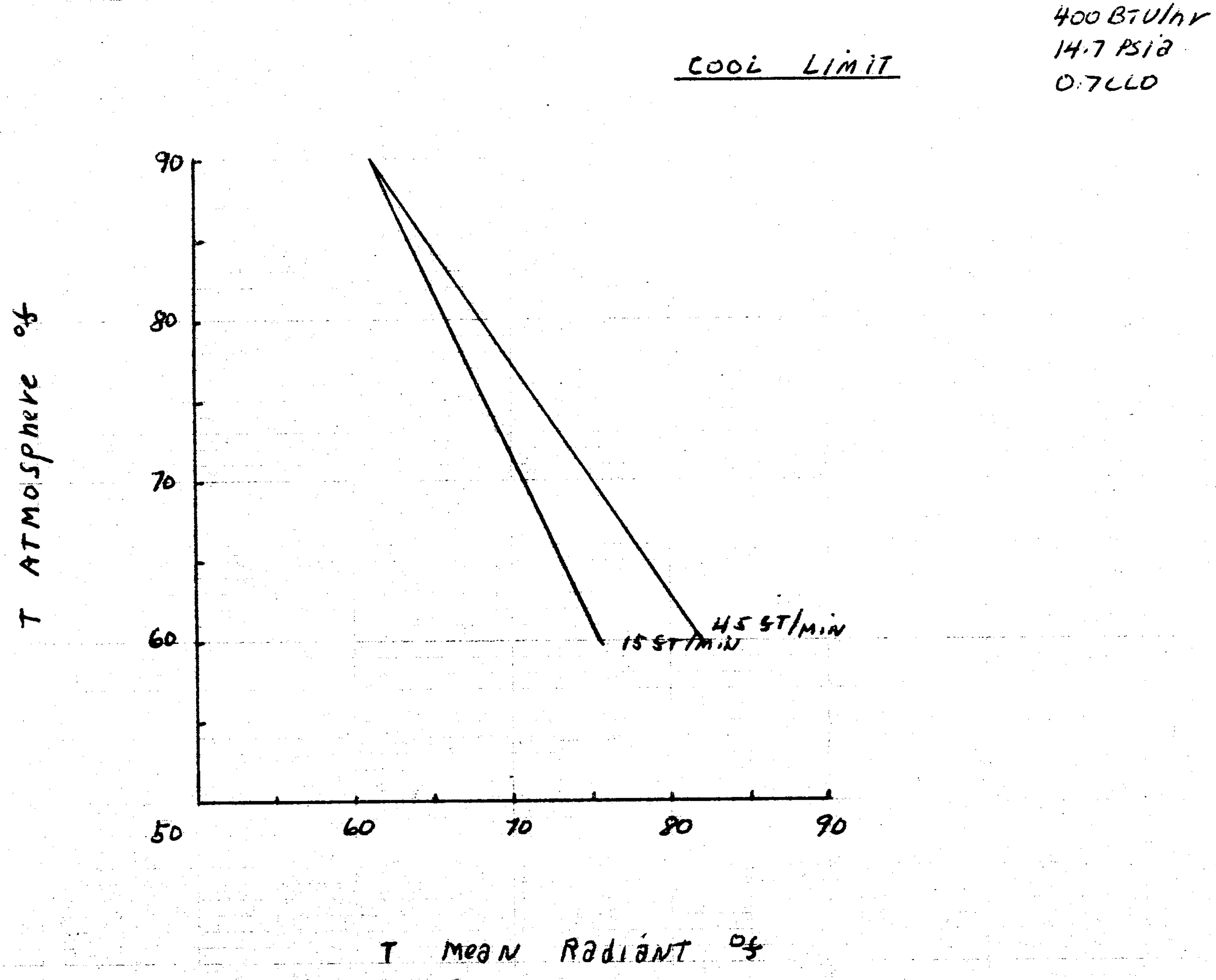
300 BTU/m.
14.7 PSIA
1.0 CLO



COOL LIMIT

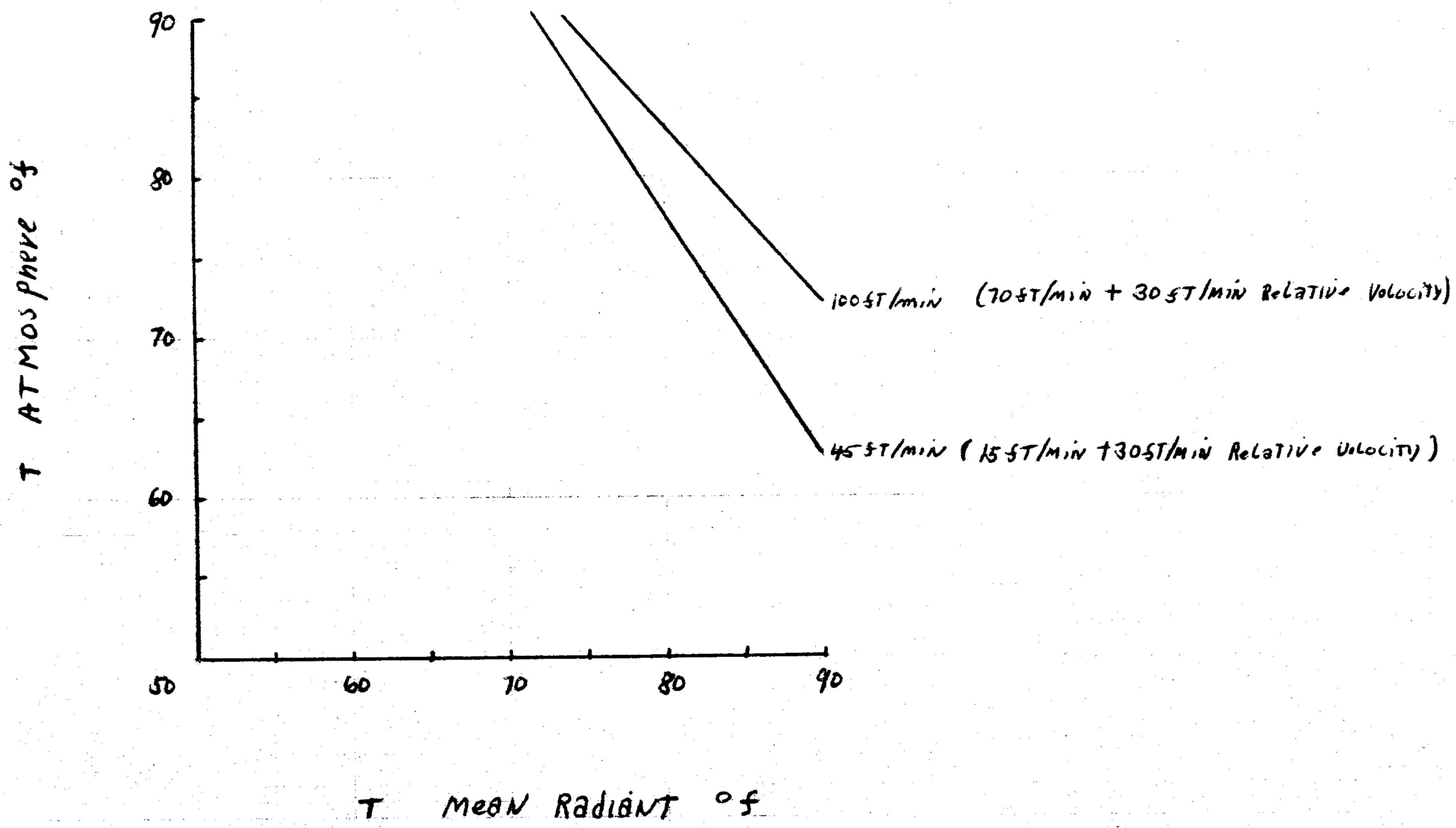
400 BTU/hr
14.7 PSIA
1.0 CLO




COOL LIMIT
400 BTU/hr
14.7 PSIA
0.7 CLO
90
80
70
60
50
60
70
80
90
15 ST/MIN
45 ST/MIN
T ATMOSPHERE °F
T MEAN RADIANT °F

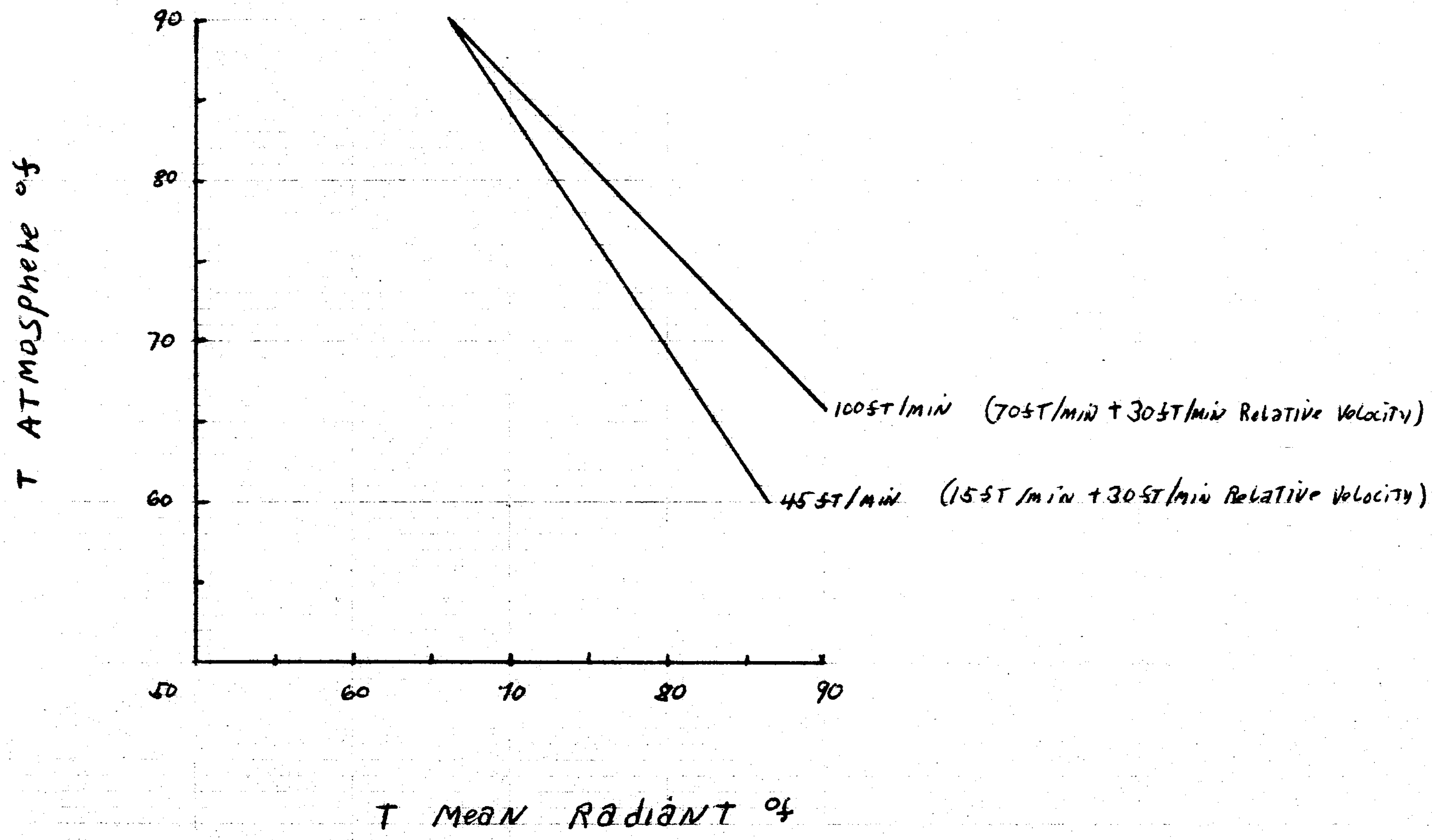
WARM LIMIT

600 BTU/hr
14.7 PSIA
0.35 CLO

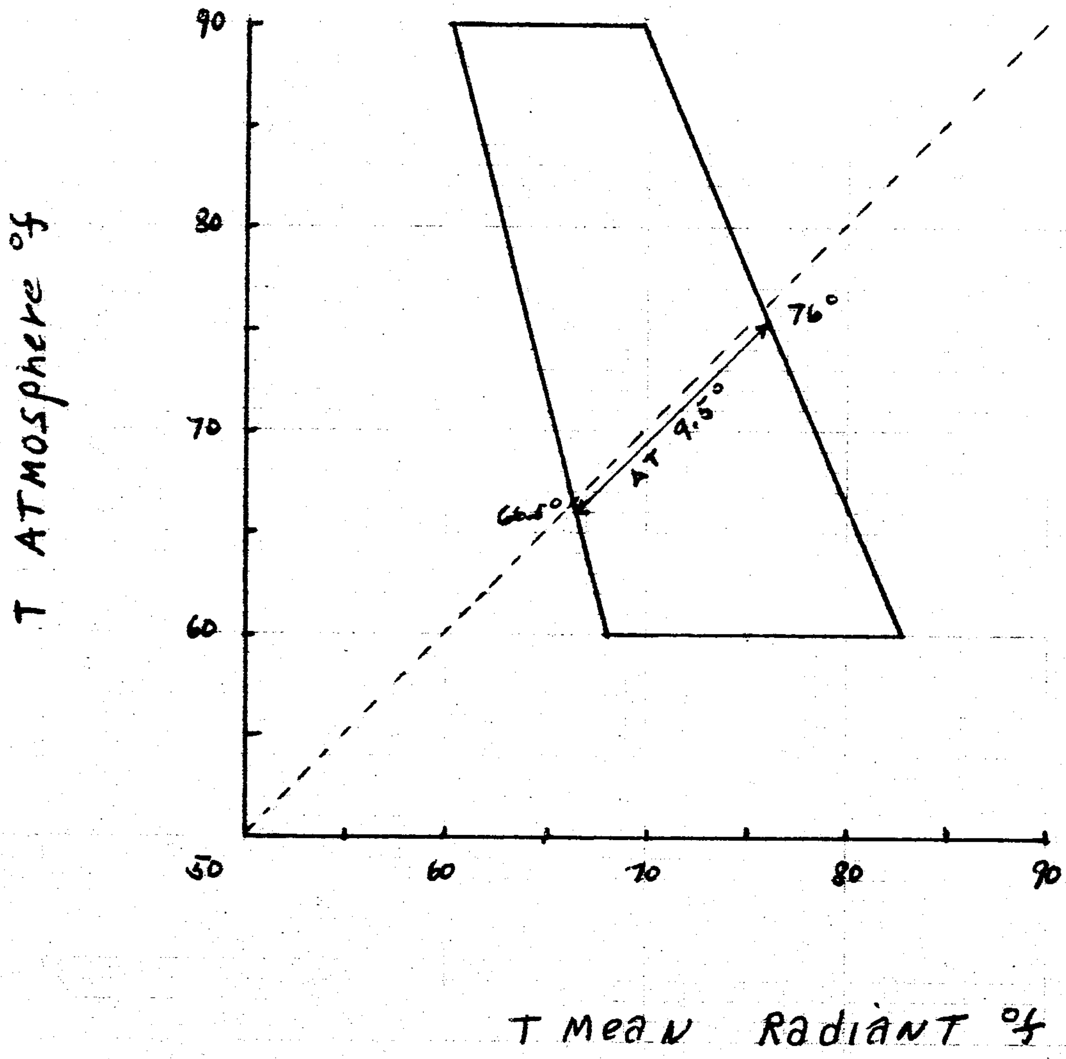


WARM LIMIT

600 BTU/hr.
14.7 psia
0.7 CLO



5.0 psia Example Comfort Envelope



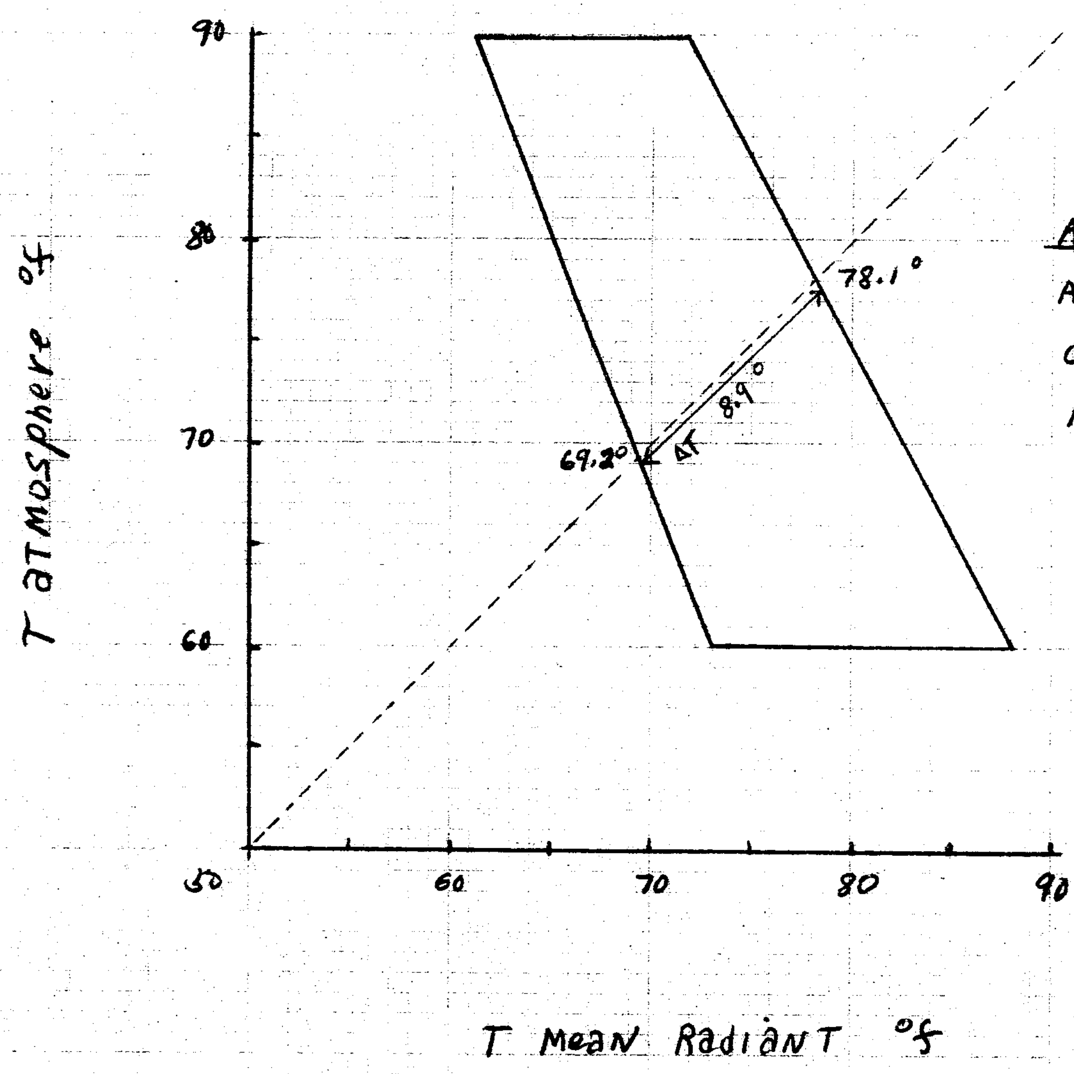
ASSUMPTIONS:

Air Motion Constant at 15 ft/min

CLO can be Varied from 0.35 to 1.0

Metabolic Rates of 300 To 600 BTU/hr.

10.0 psia Example Comfort Envelope



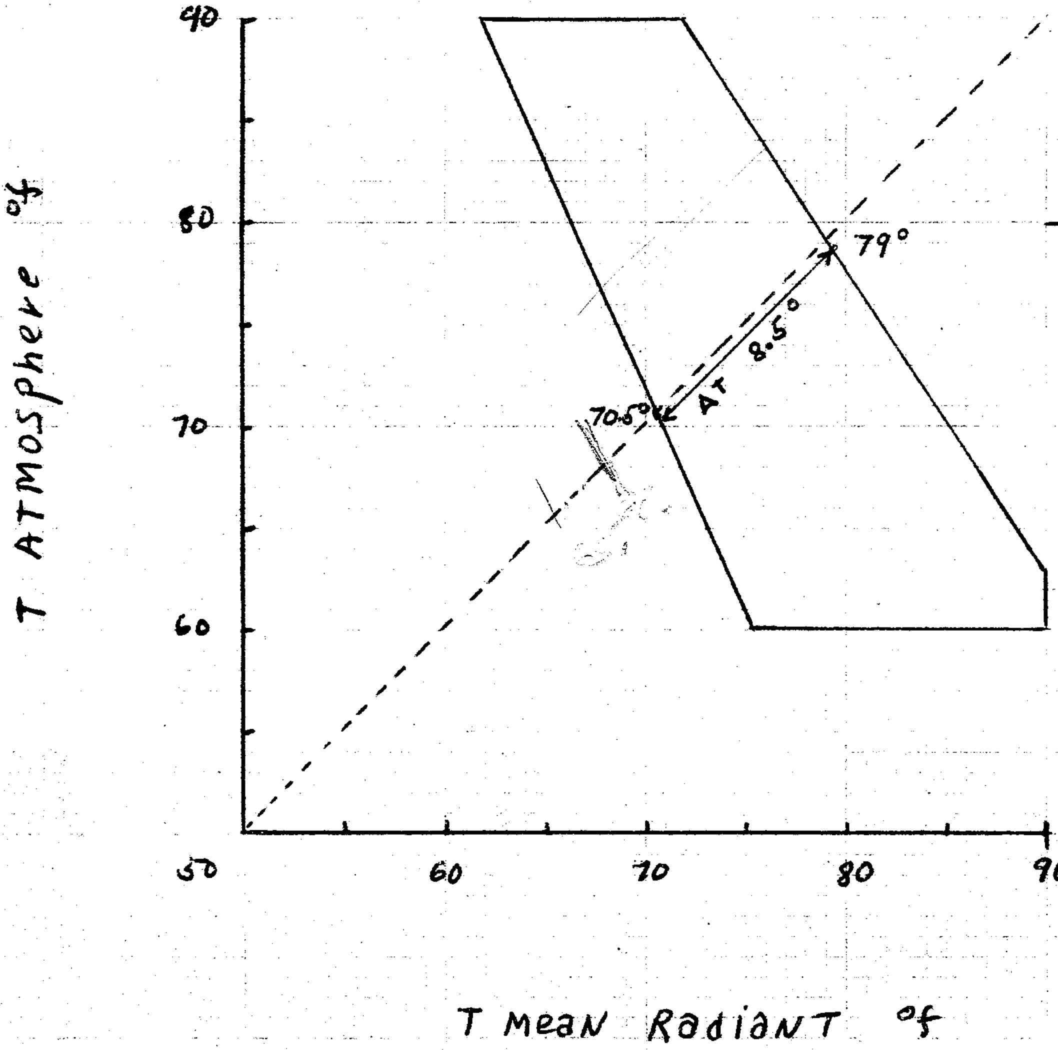
Assumptions:

Air motion constant at 15 ft/min

Clo can be varied from 0.35 to 1.0 clo

Metabolic rates of 300 to 600 BTU/hr.

14.7 PSIA Example Comfort Envelope



ASSUMPTIONS:

Air motion constant at 15 FT/MIN

CLO can be varied from 0.35 to 1.0 CLO

Metabolic rates of 300 to 600 BTU/hr.